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WIND TUNNEL MODELING STUDY OF THE DISPERSION OF SULFUR DIOXIDE IN SOUTHERN ALLEGHENY COUNTY, PENNSYLVANIA

U.S. Environmental Protection Agency
Region III
Philadelphia, Pennsylvania 19106

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WIND TUNNEL MODELING STUDY OF THE DISPERSION OF SULFUR DIOXIDE IN SOUTHERN ALLEGHENY COUNTY, PENNSYLVANIA

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THIS REPORT presents the results of a wind tunnel model study to determine the ground level SO2 concentrations in the Clairton Area of Allegheny County, produced by emissions from stationary sources within the area. The study was designed to provide data under flow conditions which correspond roughly to those which prevailed during an air pollution episode at Liberty Burough, Clairton in January 1973. The inventory of emission sources used in the tests correspond to the estimated 1973 full-scale inventory for 49 sources which were located within the confines of the modeled area.

The test program included flow visualization studies and quantitative measurements of ground-level concentrations of a tracer gas from which full-scale SO2 concentrationscould be calculated. The concentration level measurements were performed for four wind directions. At each wind direction, three wind speeds were studied with neutrally stable flow, and for one of these a temperature inversion condition was also tested.

The report presents details of the model scaling laws, the test facilities, the model, test procedures, and the experimental results. Results include measurements of the velocity and temperature profiles at several locations above the model as well as ground level concentrations.

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ABSTRACT

This report presents the results of a wind tunnel model study to determine the ground-level SO_2 concentrations in the Clairton Area of Allegheny County, produced by emissions from stationary sources within the area. The study was designed to provide data under flow conditions which correspond roughly to those which prevailed during an air pollution episode at Liberty Burough, Clairton in January 1973. The inventory of emission sources used in the tests corresponded to the estimated 1973 full-scale inventory for 49 sources which were located within the confines of the modeled area.

The test program included flow visualization studies and quantitative measurements of ground-level concentrations of a tracer gas from which full-scale SO_2 concentrations could be calculated. The concentration level measurements were performed for four wind directions. At each wind direction, three wind speeds were studied with neutrally stable flow, and for one of these a temperature inversion condition was also tested.

The report presents details of the model scaling laws, the test facilities, the model, test procedures, and the experimental results. The results include measurements of the velocity and temperature profiles at several locations above the model as well as ground-level concentrations. The latter are presented in terms of full-scale SO_2 concentrations.

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I. INTRODUCTION

This report presents the results of a model study to determine the dispersion of stack emissions over a strip of land located near the Monongahela River in the Clairton area Southeast of Pittsburgh. The objective of the study was to determine ground level concentrations of the stack effluents from steel mills and power plants which are located in the area. Both qualitative flow visualization studies and quantitative concentration level measurements were made.

The model study was performed in the Calspan Atmospheric Simulation Facility (ASF). This specialized wind tunnel, which is described in the text, was designed for the specific purpose of modeling the wind in the lower atmosphere. During the course of the current program, the ASF was modified to include the capability of generating an elevated inversion layer over the model. The test program included studies under neutrally stable flow conditions and studies in the presence of the elevated inversion. The inventory of stack emissions used in the model tests corresponded to the estimated 1973 full-scale emission inventory for forty-nine of the stacks which fell within the confines of the modeled area.

Tests to determine ground level SO_2 concentrations were performed for three wind velocities in neutral flow and one wind velocity with an elevated inversion, for each of four wind directions. In addition, the model emission inventory was operated in separate sub-groupings of sources in order to optimize the sensitivity of the concentration measurement system and at the same time allow identification of the separate contributions from various groups of stacks. In all, a total of forty tests were performed to determine ground level concentrations of SO_2 under the various wind and stack combinations.

Each test provided quantitative concentrations of SO_2 at twenty ground level sampling points. In all of the tests, two of the sampling point locations were held fixed at locations corresponding to full-scale continuous monitoring stations at Glassport and Liberty Borough. The remaining eighteen sampling points were located on the basis of flow visualization studies to provide a satisfactory distribution of samples for determining overall ground level concentrations of SO_2. The inclusion of the two full-scale monitoring stations in the sample array for all tests allows an assessment of the effectiveness of these monitoring stations as pollution alert monitors.

In the sections that follow, the scaling criteria for the model tests are presented first. This is followed by descriptions of the test facilities, the wind tunnel model, and the test procedures. Next, the experimental results are presented in three steps. First, the flow conditions over the model are described and then the results of flow visualization studies are discussed briefly. Finally, the measured ground level concentrations are presented as a series of maps which show full-scale SO_2 concentrations in ppm calculated from the model data and the scaling laws. Some concluding remarks on the program are presented in the final section. Two appendices are attached at the end of the report. In Appendix A, a discussion of the minimum permissible Reynolds number based on ground roughness height is presented. The ground level concentration data are listed in tabular form in Appendix B.

II. SCALING CRITERIA

In attempting small-scale modeling of flows in the atmospheric boundary layer, care must be taken to ensure that all important features of the full-scale situation are represented in the model. Broadly speaking, these include the ambient wind environment, including both the mean and turbulent characteristics, as well as the local terrain. In stack emission studies such as presented here, one must also model the relevant features of the exhaust gases, namely; exit momentum, buoyancy and pollutant concentration. The dynamics of such flows involve inertial, viscous and buoyancy forces, as well as turbulent transport. The scaling criteria presented here are mathematical statements of the requirement that each of these forces be present in the same relative degree in the model as in the full-scale situation.

This section is divided into four parts. The scaling requirements for modeling the atmospheric wind are discussed in II-A. The additional scaling requirements for modeling of stack emissions are presented in II-B. This is followed by a discussion of sampling time for the model measurements in II-C. Finally, a summary of the scaling equations is presented in II-D. The following notation is used.

C = pollutant volume concentration (He in model, SO_2 in prototype) (dimensionless)

C_s = volume concentration of total stack gas (dimensionless)

g = acceleration of gravity (meters/sec^2)

ℓ = characteristic length (meters)

p = pressure (pascal = newtons/meter^2)

Q^* = mass flux of SO_2 from prototype stack (kilograms/sec)

t = time (sec)

T = temperature (°K)

$\bar{u}_a$ = reference velocity (meters/sec)

$u_{m_{ref}}$ = model reference wind velocity (meters/sec) measured 1.22 meters (4 feet) above model river

$u_{p_{ref}}$ = full-scale reference wind velocity (meters/sec) corresponding to $u_{m_{ref}}$ (i.e., full-scale wind velocity at 2926 meters above river)

u_s = stack-exit velocity (meters/sec)

u_* = friction velocity (meters/sec); $u_* = (\tau_w/\rho)^{1/2}$

V = volume (meters^3)

x = streamwise coordinate (meters)

y = horizontal cross-stream coordinate (meters)

z = vertical coordinate (meters)

z_0 = characteristic ground roughness length (meters)

η = $(\ell_p/\ell_m)(\bar{u}^2_{am}/\bar{u}^2_{ap})$

λ = SO_2 (tons per year)/He (cm^3/min) for any stack

ν = kinematic viscosity (meters^2/sec)

ρ = density (kilograms/meter^3)

ρ^* = density of SO_2 at ambient temperature

τ_w = Reynolds shear stress at the wall (pascal = newtons/meter^2)

ϕ^* = volumetric flux of He from model stack (meters^3/sec)

$(\ )_a$ = in ambient air

$(\ )_m$ = model

$(\ )_p$ = prototype

$(\ )_s$ = at stack exit

A. MODELING OF ATMOSPHERIC WINDS

The primary constraint on modeling of atmospheric flows comes from the need to ensure that the tunnel boundary layer, formed over the rough floor, conforms to the "fully-rough wall" flow criterion. When this criterion is satisfied, the mean-velocity profile is logarithmic, namely

$$\frac{\bar{u}}{u_*} = \text{const.} \times \log\left(\frac{z}{z_0}\right) \tag{1}$$

where $\bar{u}$ is the mean velocity at a height z, and the characteristic roughness length of the flow, z_0, is related numerically to some average dimension of the roughness elements on the floor.

Many have studied the general problem of simulating atmospheric winds in a laboratory facility. The conclusions reached in these studies are that the ratio of a typical length scale ℓ to the roughness length of the wind profile z_0 should be matched between the model and prototype (full-scale) approaching flows:

$$\left(\frac{l}{z_0}\right)_p = \left(\frac{l}{z_0}\right)_m \qquad (2)$$

and that the approaching model flow should be "fully rough", i.e., there should be no laminar sublayer in the tunnel boundary layer. Usually this latter criterion is satisfied when a Reynolds number based on z_0 and the friction velocity u_* is more than about 3:

$$\frac{u_* z_0}{\nu} \gtrsim 3 \qquad (3)$$

Of the two conditions, (2) and (3), it is more important to satisfy condition (3). In addition to these criteria, it is also necessary to make certain that the turbulence spectra of the tunnel flow are suitably scaled reproductions of the atmospheric flow. When these conditions are met, the wind environment in the tunnel flow is a proper representation of the atmosphere, for neutrally stable conditions.

The problem of actually generating the required flow in a laboratory facility is one that has received a great deal of attention in recent years. A wide variety of approaches is available for the development of the proper flow; these involve the use of various types of roughness elements, fences, spires, and jets transverse to the flow. At Calspan, the approach that has been used is that of a matched fence/rough floor combination (see Section III). With this technique, the appropriate logarithmic mean velocity profile as well as a turbulence spectrum representative of that in the neutral atmosphere is generated.[1-4]

In addition to the above scaling criteria for modeling of the neutrally stable atmosphere, another relationship is required when thermally stratified flows are to be modeled. A simple derivation of the scaling between model and prototype in thermally stratified flows can be obtained as follows, with the understanding that all full-scale temperatures are measured relative to the potential temperature (i.e., $T = T' - \Gamma z$ where Γ is the adiabatic lapse rate and T' is the absolute temperature).

The vertical velocity attained by unit mass of gas in a given interval of time, as a result of buoyancy, must scale with the horizontal velocity. Since the vertical acceleration is given by

$$\frac{d^2 z}{dt^2} = -\frac{g \Delta \rho_a}{\rho_a} = +g \frac{\Delta T_a}{T_a}$$

the velocity acquired in time interval Δt is $g \frac{\Delta T_a}{T_a} \Delta t$.

Taking the ratio of this to the reference velocity, we obtain

$$\frac{\Delta T_{am}}{T_{am}} \frac{\Delta t_m}{\bar{u}_{am}} = \frac{\Delta T_{ap}}{T_{ap}} \frac{\Delta t_p}{\bar{u}_{ap}}$$

Using the time-scaling relation $\frac{\Delta t_m}{\Delta t_p} = \frac{\ell_m}{\bar{u}_{am}} \frac{\bar{u}_{ap}}{\ell_p}$ we obtain

$$\frac{\Delta T_{ap}}{\Delta T_{am}} = \frac{T_{ap}}{T_{am}} \frac{\ell_m}{\ell_p} \frac{\bar{u}^2_{ap}}{\bar{u}^2_{am}} \tag{4}$$

This result is equivalent to scaling based on Richardson number in a form which may be called a bulk Richardson number, $B_o = \frac{g z_o}{u_a^2} \frac{\Delta T_a}{T_a}$. Use of the parameter B_o for a scaling law has been discussed in Reference 1. For practical purposes, the ratio $\frac{T_{ap}}{T_{am}}$ in Equation (4) is essentially unity. Thus,

$$\frac{\Delta T_{ap}}{\Delta T_{am}} \approx \frac{\ell_m}{\ell_p} \frac{\bar{u}^2_{ap}}{\bar{u}^2_{am}} \tag{5}$$

Equations (2), (3) and (4) constitute the scaling criteria for the flow approaching the model. Proper simulation of stack emissions requires that additional scaling criteria be satisfied. These are discussed below.

B. MODELING OF STACK EMISSIONS

There are three aspects to be considered regarding the scaling laws for stack emissions. These are:

(1) Exit momentum scaling
(2) Buoyancy scaling
(3) Pollutant concentration scaling

Since the current literature contains various opinions as to the proper form of the appropriate scaling laws (see for example, Reference 5), it is relevant to discuss these laws in greater detail. In the following discussion, it is a basic assumption that the model is scaled geometrically and that the distribution of eddies and eddy sizes is correctly modeled to scale (in a statistical sense) in the ASF. Then, since all properties of the flow are determined by the turbulent mixing, all other properties of the flow such as mean-velocity profile, Reynolds stress distribution, spectral energy distributions, and (in the case of stratified flow) deviations from the potential temperature will be correctly scaled. That this is so in the ASF has been demonstrated by extensive measurements in pilot studies,[2-4] which formed the basis for design of the ASF, and also during calibration of the ASF itself.

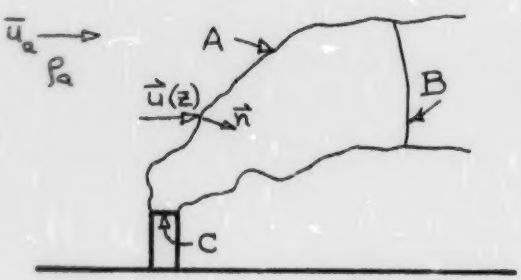
1. Exit Momentum Scaling

Near the exit of a stack, the velocity and direction of motion of any small volume of the plume depends on the ratio of the horizontal momentum given to it by that portion of it which came from the ambient wind, to the vertical momentum contributed by the stack gas. This is true in the early part of the mixing process, before buoyancy has had time to contribute significant vertical momentum. Since any model motion must correspond to a possible full-scale motion, the above momentum ratio must be the same in model and full-scale. The ambient air in the small volume may have come from different levels with, therefore, different velocities. However, these can all be expressed in terms of the momentum per unit volume at some reference height where the velocity is $\bar{u}_a$, since the fractions of gas that come from all levels, and from the stack, must be the same in the model and in full-scale. Thus, the momentum scaling near the stack exit requires that

$$\frac{\rho_{sm} u_{sm}^2}{\rho_a \bar{u}_{am}^2} = \frac{\rho_{sp} u_{sp}^2}{\rho_a u_{ap}^2} \qquad (6)$$

This result can equally well be derived by considering the average direction and momentum at any cross-section of the plume. The surface enclosing all the mixing region is denoted by A. The cross-section B is bounded by the surface A. The stack exit surface is C.

The flux of horizontal momentum, ϕ_A , entering the plume through A must flow out through B. Likewise, the flux of vertical momentum, ϕ_c , entering via the stack must also flow out through B. The ratio ϕ_c / ϕ_A must be the same in the model and in full scale.



Writing $\vec{u}(z)$ for the velocity at any height z ,

$$\phi_A = \rho_a \iint_A (\vec{u}(z) \cdot \vec{n}) |\vec{u}(z)| \, dA$$

Also, $\vec{u}(z)$ can be functionally related to the reference velocity, $\vec{u}_a$, as follows

$$\vec{u}(z) = \vec{u}_a \vec{f}(z)$$

Thus,

$$\phi_A = \rho_a \vec{u}_a^2 \iint_A (\vec{f}(z) \cdot n) |\vec{f}(z)| \, dA$$

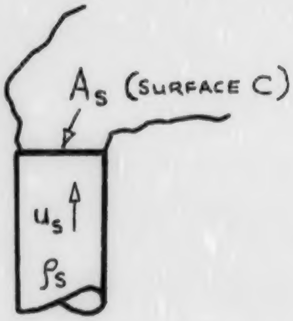
For correspondence between model and full-scale, the surface integral must be expressible in the form

$$\iint_A (\vec{f}(z) \cdot \vec{n}) |\vec{f}(z)| \, dA = const. \, \ell^2$$

where ℓ is a characteristic length.

The flux of vertical momentum is simply

$$\phi_c = \rho_s u_s^2 A_s$$



Thus, the momentum ratio becomes

$$\frac{\phi_c}{\phi_A} = \frac{\rho_s u_s^2}{\rho_a \vec{u}_a^2} \frac{A_s}{const. \, \ell^2}$$

Hence, for correspondence between the model, $(\ )_m$, and the full-scale prototype, $(\ )_p$, we must have

$$\frac{\rho_{sm} u_{sm}^2}{\rho_a \bar{u}_{am}^2} \frac{A_{sm}}{l_m^2} = \frac{\rho_{sp} u_{sp}^2}{\rho_a \bar{u}_{ap}^2} \frac{A_{sp}}{l_p^2}$$

where we have assumed $\rho_{am} = \rho_{ap} = \rho_a$

Since $\frac{A_{sm}}{A_{sp}} = \frac{l_m^2}{l_p^2}$ the relation becomes, as before,

$$\frac{\rho_{sm} u_{sm}^2}{\rho_a u_{am}^2} = \frac{\rho_{sp} u_{sp}^2}{\rho_a \bar{u}_{ap}^2} \tag{6}$$

2. Buoyancy Scaling

As the plume from a stack diffuses downstream, its motion must become buoyancy dominated. The velocity and direction of motion of any small volume, ΔV , is determined by the ratio

$$\frac{\text{Stream momentum in } \Delta V}{\text{Buoyancy momentum in } \Delta V}$$

In a volume ΔV of the plume, a fraction C_s is stack gas and a fraction $(1-C_s)$ is entrained air. The entrained air may have originated at many different heights, but its velocity will be some function of position and time and may be written as a function of the reference velocity $\bar{u}_a$. Thus,

$$\text{Stream Momentum in } \Delta V = \Delta V (1-C_s) \rho_a \bar{u}_a f_1(x, y, z, t)$$

The buoyancy momentum in the volume ΔV is calculated as the impulse delivered by buoyancy to the fraction C_s in its travel to the location (x, y, z) at time t. If we consider ΔV small enough, then all of the fraction C_s may be considered as having traversed the same route. The time taken to traverse this route may be written as a space and time function of the characteristic time scale, $l/\bar{u}_a$.

Thus, the buoyancy force on $\Delta V = \Delta V\, C_s\, g(\rho_s - \rho_a)$ and it has acted for a time = $f_2(x, y, z, t)\, \ell/\bar{u}_a$ producing the

$$\text{Buoyancy Momentum in } \Delta V = \Delta V C_s\, g(\rho_s - \rho_a) f_2(x,y,z,t) \frac{\ell}{\bar{u}_a}$$

Thus, the ratio

$$\frac{\text{Stream Momentum in } \Delta V}{\text{Buoyancy Momentum in } \Delta V} = \frac{1-C_s}{C_s} \frac{\rho_a \bar{u}_a^2}{(\rho_s - \rho_a) g \ell} \frac{f_1(x,y,z,t)}{f_2(x,y,z,t)}$$

Since the model motion must be a possible full-scale prototype motion, this ratio must be the same in the model and prototype at corresponding points in space and time. Furthermore, the functions f_1 and f_2 must have the same numerical values in the model and prototype at corresponding points in space and time because they are geometrical functions of the scaled motion. Thus, the scaling relationship becomes

$$\frac{1-C_{sm}}{C_{sm}} \frac{\rho_a \bar{u}_{am}^2}{(\rho_{sm} - \rho_a)\ell_m} = \frac{1-C_{sp}}{C_{sp}} \frac{\rho_a \bar{u}_{ap}^2}{(\rho_{sp} - \rho_a)\ell_p}$$

Generally, where buoyancy dominates $C_s << 1$ and the relation can be written

$$\frac{\bar{u}_{am}^2}{\bar{u}_{ap}^2} = \frac{C_{sm}}{C_{sp}} \frac{1 - \frac{\rho_{sm}}{\rho_a}}{1 - \frac{\rho_{sp}}{\rho_a}} \frac{\ell_m}{\ell_p} \qquad (7)$$

To find a relation for the ratio of the stack-gas concentration in the model to that in the prototype, we may simply observe that stack-gas concentration must be proportional to stack exit velocity and, far downstream, inversely proportional to stream velocity. Thus

$$\frac{C_{sm}}{C_{sp}} = \frac{u_{sm}}{u_{sp}} \frac{\bar{u}_{ap}}{\bar{u}_{am}} \qquad (8)$$

More formally, we may again consider a cross section, B, of the plume - say, a vertical cross section. The flux of stack gas through B must equal the flux emanating from the stack. That is

$$\overline{\iint_B C_s(x,y,z,t)\, u(x,y,z,t)\, dB} = u_s A_s$$

where the bar denotes time averaging.

Again, writing C_s and u as functions of some reference concentration and velocity

$$C_{ref}\,\bar{u}_a \overline{\iint_B f_s(x,y,z,t)\,dB} = u_s A_s$$

Invoking the necessary correspondence between model and full scale, and noting that $\iint_B f_s\,dB$ is proportional to ℓ^2, since $\frac{C_{sm}}{C_{sp}} = \frac{C_{ref\,m}}{C_{ref\,p}}$ and $\frac{A_{sm}}{A_{sp}} = \frac{\ell_m^2}{\ell_p^2}$ we have

$$\frac{C_{sm}}{C_{sp}} = \frac{u_{sm}}{u_{sp}}\,\frac{\bar{u}_{ap}}{\bar{u}_{am}} \tag{8}$$

as before.

Finally, combining equations (7) and (8), the following equation is obtained,*

$$\frac{\bar{u}_{am}^3}{\bar{u}_{ap}^3} = \frac{u_{sm}}{u_{sp}}\;\frac{1-\dfrac{\rho_{sm}}{\rho_a}}{1-\dfrac{\rho_{sp}}{\rho_a}}\;\frac{\ell_m}{\ell_p} \tag{9}$$

In practice, this equation is usually combined with the momentum scaling equation (6) to give

$$\frac{\bar{u}_{am}^2}{\bar{u}_{ap}^2} = \sqrt{\frac{\rho_{sp}}{\rho_{sm}}}\;\frac{1-\dfrac{\rho_{sm}}{\rho_a}}{1-\dfrac{\rho_{sp}}{\rho_a}}\;\frac{\ell_m}{\ell_p} \tag{10}$$

leading finally to

$$\frac{\bar{u}_{am}^2}{\bar{u}_{ap}^2} = \frac{\sqrt{\dfrac{\rho_a}{\rho_{sm}}} - \sqrt{\dfrac{\rho_{sm}}{\rho_a}}}{\sqrt{\dfrac{\rho_a}{\rho_{sp}}} - \sqrt{\dfrac{\rho_{sp}}{\rho_a}}}\;\frac{\ell_m}{\ell_p} \tag{10a}$$

This equation determines the model stack density for any choice of the parameter

$$\eta \equiv \frac{\ell_p}{\ell_m}\,\frac{\bar{u}_{am}^2}{\bar{u}_{ap}^2} \tag{11}$$

Ordinarily, it is not necessary to scale the volumetric (or mass) flux at the stack exit, and no further restriction need be imposed on the scaling of the dynamics of the plume.

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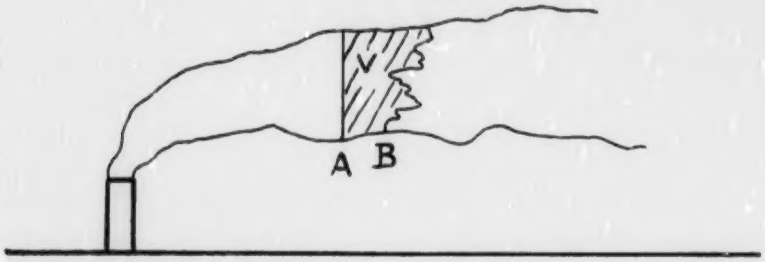
*Equation (9) can be shown to be in agreement with the buoyant plume rise relation recommended by Briggs (Reference 6, equations 4.19c and 4.32) and with the relation for touchdown point of negatively buoyant plumes advanced in Reference 7 (equation 6.3). Moreover, the maximum plume rise of negatively buoyant plumes (Reference 7, equation 6.2) scales in accordance with equations (6) and (9) above.

Equation (10) indicates that the wind velocity over the model must be reduced in proportion to the square root of the geometric scale ratio between the model and full-scale. In many situations, it is necessary to model relatively large areas and the geometric scale ratio must be chosen so that the area will fit in the wind tunnel. This may require values of ℓ_m/ℓ_p which are very small, say on the order of 1/2000. Then, it becomes desirable to increase the values of the other terms in Equation (10) so that the required model wind velocities do not become so small that Equation (3) cannot be satisfied. This is done using highly buoyant gas mixtures for the model stack effluents. It can readily be seen from Equation (10) that a decrease in ρ_{sm} will increase u_{am} for given values of the other variables. In other words, the buoyancy and inertial forces must not only be in the proper ratio, but must be large enough in absolute terms to keep the influence of molecular viscosity negligible, and satisfy Equation (3). This results in an envelope or "window" of experimental conditions within which one must operate to simulate the full-scale flow properly.

3. Pollutant Concentration Scaling

The inventory for full scale stack emissions usually gives pollutant fluxes in mass/unit time. In the model we deal with He fluxes in volume/unit time. For any stack let the full-scale mass flux of SO_2 be Q^* and the model volume flux of He be ϕ^*. The density of SO_2 at ambient temperature is ρ^*.

A very simple derivation of the concentration scaling law can be obtained as follows. At some instant mark a cross section of the plume, A. Let a short time, t, pass and observe the new position of the cross section, B. A volume, V, is contained between A and B. Since the model motion must be a possible full-scale motion, we can look at this same picture on both scales and say the following.



The transient times between A and B are not the same for the two scales. They are related as follows.

$$\frac{t_p}{t_m} = \frac{\ell_p}{\bar{u}_{ap}} \frac{\bar{u}_{am}}{\ell_m} \tag{12}$$

where $\bar{u}_a$ is the reference velocity, and ℓ is a characteristic length. The volumes, V, also differ

$$\frac{V_p}{V_m} = \frac{\ell_p^3}{\ell_m^3} \tag{13}$$

The average concentration of SO_2 in the prototype volume is given by

$$\bar{c}_p = \frac{Q^*}{\rho^*} \frac{t_p}{V_p} \tag{14}$$

Note that, since we are primarily concerned with the far field where the plume is near ambient temperature, we use the SO_2 density, ρ^*, at ambient temperature. The average concentration of He in the model volume is given by

$$\bar{c}_m = \phi^* \frac{t_m}{V_m} \tag{15}$$

Equations (12) through (15) can be used to obtain the ratio $\bar{c}_p/\bar{c}_m$. Since the initial cross section, A, was completely arbitrary, this ratio must also hold for all values of C_p/C_m at corresponding points in model and prototype. Thus,

$$\frac{c_p}{c_m} = \frac{Q^*}{\rho^* \phi^*} \frac{\ell_m^2}{\ell_p^2} \frac{\bar{u}_{am}}{\bar{u}_{ap}} \tag{16}$$

Equation (16) is written in a form consistent with the relaxation of the volumetric (or mass) flux modeling law, as mentioned following Equation (11), and thus may seem unfamiliar at first.

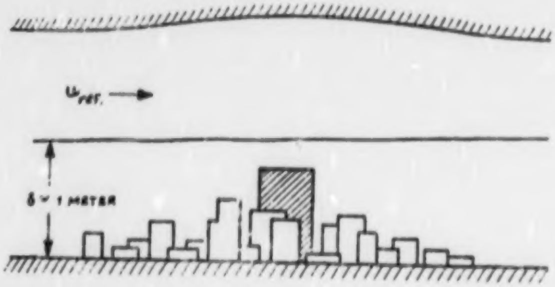
C. SAMPLING TIME

A final discussion, regarding the comparison of model results with full scale, relates to the well-known fact that in full-scale the averaging time has a distinct effect on the measured concentrations. This is not the case in model tests in the ASF. The model results correspond to short-time averaged full-scale measurements, taken over not more than 10 or 15 minutes in most cases. Briefly, what is involved here is the following. The frequency spectrum of wind gusts in full-scale always shows a null, or near null, in the range 1 to 3 cycles per hour.[8] Thus, it is theoretically correct to separate the spectrum into two parts at a frequency in that range, and deal with phenomena associated with each part separately. In the ASF the high-frequency portion related to the ground-induced turbulence is fully simulated. The low-frequency portion related to meandering of the wind, diurnal fluctuations, passage of weather systems, annual changes, and so on, must be considered separately. In particular, a correction[9,10,11] for meandering of the wind can be applied if necessary, to compare with longer term averaging. Thus, since the effective full-scale averaging time is independent of model averaging times, one can choose the model averaging time to provide data which are repeatable to within a specified accuracy. The model averaging times required to obtain a given accuracy can be estimated from statistical considerations as described in the following paragraphs. However, as noted above, the data so obtained will correspond to full-scale data measured over not more than 10 to 15 minutes.

For a statistically stationary process one can form an average of any quantity by taking N independent samples, adding their values and dividing by N. If one were to do this many times, one would obtain a distribution of average values having some standard deviation from the true mean. The ratio of this standard deviation to the true mean value is approximately $N^{-1/2}$, in most cases. This ratio may be regarded as a typical fractional error in a quantity measured by averaging N independent samples. Thus, to keep this error within 10% of the mean requires about 100 samples; to keep it within 1% requires about 10,000 samples.

We have stressed that the samples must be independent. That means that that the system (the air flow around the model in the ASF) must "forget" what it was doing in the time span between samples -- an independent sample can be obtained once the correlation with the last value has essentially vanished.

Now we do not actually sample at long intervals, as indicated above. We generally deal with continuous data or with digitized data taken at a high sampling rate. However, we are still essentially bound by the same rules, and to estimate the required averaging time we can proceed along the following lines. The model is immersed in a boundary layer of thickness, δ , typically about 1 meter. The velocity, u_{ref} , near the top of the boundary layer may be anything from roughly 1 to 25 meters per second. The biggest eddies in the turbulent flow essentially span the boundary layer, so that we are not assured of an independent turbulence picture until the boundary layer has moved a distance of about δ . We can say that most of the boundary layer moves at a velocity close to u_{ref} , so we can take "independent" samples at a rate u_{ref}/δ per second. We can now construct an equation which relates the sampling time, t, required to obtain a given fractional error, σ , to the tunnel reference velocity, u_{ref} . From the above discussion,



$$\sigma \approx \frac{1}{\sqrt{N}} \quad \text{and} \quad N \approx t_s \frac{u_{ref}}{\delta}$$

Thus,

$$t_s \approx \frac{\delta}{u_{ref}\,\sigma^2} \qquad (17)$$

where

t_s = model sampling time
δ = ASF boundary layer thickness ($\approx$ 1 meter)
u_{ref} = ASF reference velocity at top of boundary layer
σ = fractional error in measurements (% error/100)

It should be noted that, in the case of turbulence measurements, high frequency components require the same averaging time as discussed above because they are the products of the breakdown of the large (low frequency) eddies. Therefore, they are subject to the same statistical considerations.

As indicated in the derivation, Equation (17) is only approximate. In practice, it has usually been found that somewhat shorter averaging times provide the required accuracy. To establish a suitable value at the start of any program, a few averages are generally checked as a function of integration period.

D. SUMMARY

The basic scaling criteria used in this investigation can be summarized as follows.

Ground Roughness Reynolds Number - Equation (3)
Temperature Inversion - Equation (5)
Stack Exit Momentum - Equation (6)
Stack Emission Buoyancy - Equation (10)
Pollutant Concentration - Equation (16)
Approximate Sampling Time Required - Equation (17)

In addition, Equation (2) which relates a typical length scale to the characteristic roughness length of the ground is satisfied approximately in the ASF in that (i) geometric scaling for the model is used, and (ii) the approach flow to the model is developed over a considerable length of random roughness elements whose mean height is scaled to the full-scale terrain upwind of the modeled area.

III. TEST FACILITIES

A. THE ATMOSPHERIC SIMULATION FACILITY

The Calspan Atmospheric Simulation Facility (ASF), is designed mainly for studying atmospheric flow phenomena. This wind tunnel differs from the conventional aeronautical wind tunnel in two important respects, namely, the wind shear and the degree of turbulence. Every effort is made in a conventional aeronautical wind tunnel to assure a smooth, uniform flow, free from turbulent gusts. In contrast to this, a wind tunnel for simulating the lower atmospheric flow requires a relatively thick turbulent boundary layer within which the mean and turbulent properties are similar to those in the atmosphere.

In order to simulate these effects properly, a wind tunnel must be constructed in a very unconventional way. The particular method developed at Calspan for this purpose[1-4] is to use a fence, protruding from the floor of the tunnel, followed by a length of floor that is covered with roughness elements. This combination assures both the desired shear, and the associated turbulent gust spectrum as well. Figure 1 shows an exterior view of the facility. The rough floor, consisting of wooden blocks in this case, can be seen upstream of the model in Figure 2. The fence, which is a solid aluminum plate, protruding from the floor at the beginning of the flow development region, is also visible in this figure.

The facility is 36 meters long. The test flow is developed generally over a length of about 15 m downwind of the intake, leaving approximately 9 m available as a test section. The tunnel test section is 2.4 m wide by approximately 2.1 m high. The tunnel ceiling is adjustable to allow the axial pressure gradient to be set near zero. The turbulent shear layer occupies roughly the lower meter of the test section. A variable-pitch fan powered by a two-speed motor pulls air through the tunnel at speeds from less than 0.5 meter/second to 25 meters/second.

Two turntables are incorporated into the floor of the ASF. Both of them have a diameter of 2.24 meters. These turntables can be located at various axial locations. In the current program, the center of the turntable used was located 15.9 meters from the beginning of the flow development region.

For the present series of tests a liquid-nitrogen (LN_2) delivery system was installed above the ASF. To produce temperature-inversion conditions, LN_2 was poured from four sintered-metal vapor-phase separators through holes two abreast in the ceiling of the ASF near the beginning of the flow development region. Each pair of LN_2 streams fell onto a metal plate covered with wooden blocks similar to those of the rough ground. The LN_2 scattered fairly uniformly over the two plates. As the LN_2 evaporates, it both cools the air and adds cold N_2 to the flow.

B. POLLUTANT-CONCENTRATION MEASURING SYSTEM

The most common application of the ASF to pollution dispersion is related to the emission from multiple sources (stacks) in an industrial area. These emissions are generally hot and have reasonably high exit velocities. As discussed in Section II, it is necessary to simulate the proper stack emission buoyancy, exit momentum, and pollution content. This is done by using gas mixtures to simulate the emission from each stack. The mixtures are made up of nitrogen, helium, and hydrogen. The helium in the gas mixtures is the pollutant simulant and the mass flow of helium is made proportional to the mass flow of pollutant (SO_2 in this program). The nitrogen and hydrogen components in the gas mixtures are adjusted to provide the correct buoyancy and exit momentum for the stack emissions.

In the current study, forty-nine stacks were simulated at a scale ratio of 1:2400. The gas flow rates required to make the emission gas mixtures were very small, so it was not possible to use conventional flow meters or metering valves. Instead, the component mixtures were generated by metering gases through capillary tubing trimmed to the required flow rate with an internal length of piano wire. The complete gas generating system consisted of three regulated gas supplies, H_2, He and N_2 at 5.9×10^4 pascal gauge (8.5 psig), and a network of calibrated capillaries to connect each stack, or group of stacks, to the gas supplies. Stacks were grouped together wherever several stacks had the same, or nearly the same emissions. A single set of two or three calibrated capillaries could then serve to regulate the flows for the group. In these cases the distribution to the group was through sufficient lengths of tubing to ensure that each stack received an equal share. Pressure differentials generated by the boundary-layer flow over the model are so small, at the low speeds used in these studies, as to be completely negligible.

The emission-gas generating system was used in conjunction with a multiple channel sampling system to determine concentrations of pollutant (helium) at various points downstream from the stacks. The concentration sampling system is illustrated in Figure 3 where it is shown connected to a helium leak detector which is used for quantitative analysis. Briefly, the sampling system consists of a ring of 24 chambers (the numbered cylinders on the left of Figure 3), which are initially pumped down to a hard vacuum, into which the samples are drawn through 3.7 meter long capillaries. Three of these capillaries were taken to calibration gases, viz.

(1) dry N_2 containing about 1 ppm He
(2) 50 ppm He in Air
(3) 975 or 1078 ppm He in Air (according to gas analysis)

The reference mixtures and their analyses were supplied by the Matheson Company. The other capillaries were exposed to the mixtures drawn from the 20 sampling points on the model and one upstream reference to determine background level.

Each capillary is connected to the top of a sample collection chamber through a solenoid valve electrically driven so that all 24 solenoids can be opened or closed simultaneously. The bottom of each collection chamber is open to a vacuum plenum which is held at roughly 10^{-5} torr by a diffusion pump backed by a large mechanical pump. A single plate valve is used to seal off all 24 chambers from the vacuum plenum at the start of sample collection in the chambers.

The method of collecting the samples is as follows. The collection chambers are pumped down to a hard vacuum ($\approx 10^{-5}$ torr) with the capillary end of the chambers closed by the solenoid valves. Then with the conditions for a test established (stacks operating and capillaries exposed to the proper calibration gases and flows to be sampled), the capillaries are flushed for 15 seconds by opening the solenoid valves. This is sufficient time to draw legitimate samples into the full lengths of the capillaries. The solenoid valves are then closed and the chambers are pumped down to a hard vacuum. This takes about 15 seconds. During this time the capillaries return to atmospheric pressure but they now contain legitimate samples. Once the hard vacuum is attained in the chambers, the large plate valve at the bottom of the chambers is closed to seal off all 24 chambers from the vacuum plenum. Finally the solenoid valves are reopened for 300 seconds to allow samples into the chambers. The solenoid valves are then closed to seal the collection chambers which now contain the collected samples at a final pressure of 1 or 2 torr.

At the end of sampling, each chamber is analyzed for helium concentration by connecting it, in turn, to the measuring system through an electrically driven scanning valve. The measurement is made on a helium leak detector in which the pressure is regulated by the fixed geometrical (area) relationship between an inlet pinhole at the scanning valve and the outlet restriction of a butterfly valve which is part of the leak-detector. Since each sample chamber is at the same pressure, the leak detector provides a direct reading of the concentration level.

The system has been trimmed so that, when all channels are exposed to the same source, the readouts lie within ±5% of the mean, down to concentrations of about 5 ppm helium. Trimming was done by adjusting the capillary flows. The capillaries are 3.7 meters long and have a nominal internal diameter of .051 cm. They were threaded with lengths of .041 cm diameter piano wire. The length of each wire was adjusted to effect the trimming of the flow rate. Thus the leak detector always sees the same pressure, about 10^{-4} torr, and its readings depend only on the concentration of helium. Calibration mixtures in the 3 calibration channels allow direct standardization on each scan. The response time is governed by the time to flush the volume between the pinhole and the butterfly, which is a few seconds. About 10 seconds averaging was used to obtain repeatable results. An automatic electronic control, activated when the sample channel is switched, waits for a selected time to allow for equilibration, then integrates the output for whatever number of seconds is selected. A complete scan of the 24 channels took about 10 minutes. At the lowest concentrations some time is required to get complete "clean-up" of helium in the system if it has just been used at much higher concentrations. The overall performance can be relied upon to within ±10% down to 5 ppm. With special care, even greater precision can be achieved.

Since the system uses a buoyant constituent (helium) as the pollution simulant gas, large percentages can be used and the equivalent sensitivity to SO_2 at full scale is much greater than the actual sensitivity to He at model scale. Another advantage of using He as the simulant is that the background concentration in normal air is low, generally about 5-1/4 ppm. The resolution of the equipment, defined as that concentration which produces a reading equal to the maximum random fluctuation, is at least 1/2 ppm, but the system must be kept extremely clean, and adequate time must be allowed for the system to equilibrate at each reading, if one intends to utilize it to its full capability. In this study the ratio of full scale ppm SO_2 to model ppm He ranged from 6×10^{-4} to 3×10^{-3}. It was our objective to maintain a resolution of .01 ppm SO_2 or better. This required a He resolution in the model measurements ranging from 17 ppm when simulating the Clairton and Irvin complexes to 3 ppm when simulating the Claus plant, Mitchell and Elrama simulations being intermediate. Thus, in general, the system capability was not fully taxed so that moderately fast sampling was possible for most measurements while maintaining a full-scale resolution of considerably better than .01 ppm SO_2. The system resolution finally attained in this program is discussed in Section IV-D.

C. AUXILIARY EQUIPMENT

One of the problems encountered in modeling of stack emissions in the ASF is the lack of reliable instruments to measure the very low velocities required by the scaling laws. Such measurements are usually made with hot-wire anemometers. However, the calibration of these instruments is dependent on the temperature as well as the velocity of the flow. When the flow temperature varies with position (in the flow), for example, when modeling an inversion, hot-wire techniques for determining flow velocity become difficult and time consuming. Thus, it was decided to take a different approach to velocity measurements in the presence of a model temperature inversion. A heat-pulse anemometer, developed at Calspan, was used for this purpose. This instrument operates as follows.

A hot-wire, similar to a conventional hot-wire anemometer, is raised in temperature step-wise 100 times per second. It is maintained at a constant elevated temperature for 0.5 millisec. It can be shown theoretically[12] that if the heat transport is mainly by convection rather than conduction (large Peclet number), then the temperature jump at any point downstream is affected symmetrically by the diffusion process, and the mid-point of the jump occurs at a time determined by fluid velocity and the distance from the heated wire to the point. That is, the mid-point, or point of inflection, is independent of the thermal properties of the fluid.

The Calspan heat-pulse anemometer consists of two fine wires at right-angles to each other, and to the mean flow velocity. The upstream wire is pulsed electrically and the downstream wire acts as the temperature sensor. A signal-processing circuit determines each transit time as described above, rejecting any unsatisfactory measurements, and integrates over 1,000 samples (i.e., for approximately 10 seconds) to produce a voltage proportional to the average velocity. Lacking a longer-term integration period we have generally summed about 5 or 6 readings to obtain a more useful average.

Calibration of the heat-pulse anemometer was accomplished by placing it in a uniform flow and comparing its output with the flow velocity. The flow velocity was determined from the measured time of passage of a smoke puff between two streamwise locations in the flow. The useful range of the velocity calibration depends on the distance between the pulsed wire and the sensor wire in the heat pulse anemometer. The particular instrument used in this program had a useful calibrated range between approximately 0.15 m/sec and 0.5 m/sec.

In addition to the use of the heat-pulse anemometer for measuring flow velocities in the modeled inversion layer, temperature profiles in the layer were measured with a rake of thermistors. The thermistor rake is apparent on the lower right side of Figure 2. This rake is mounted on a traversing mechanism which can be positioned anywhere in the ASF test section. The rake has an attachment point on the bottom for the heat pulse anemometer. The combined rake system was used to obtain the required temperature and velocity profiles.

Finally, the smoke puff technique was used to measure reference velocities in the approximately uniform flow 4 feet (1.22 meters) above the model river level.

IV. WIND TUNNEL MODEL

In general, it is desired that the model be designed to be as versatile as practicable. However, the scaling and mechanical construction problems associated with building a model to simulate a large full scale area introduce certain limitations which are discussed in the following paragraphs.

The Clairton Model SO_2 Inventory supplied to Calspan indicated that there are 49 emission sources of varying degrees of importance along the Monongahela River. These sources are generally distributed along a strip of land about five kilometers wide by twenty kilometers long with its long axis running approximately parallel to the N.E. direction.

As will be shown, it was not possible to select a model scale sufficiently small to allow this entire area to be modeled within the confines of the turntable of the ASF. However, it is desirable to incorporate as much of the area as possible on the turntable, so that, when the upstream details are not sufficiently unique to require specific modeling, the general rough ground can be continued up to the turntable which can then simply be rotated to change wind direction. Additional sources and terrain can be added upstream for those wind directions where they are required. The location of the center of the turntable and the extent of detailed modeling for each wind direction is given later in this section. The following paragraphs (Section IV-A) are concerned with the selection of the smallest permissible scale ratio between the model and the prototype. The model construction is presented in IV-B and the source inventory and their locations are given in IV-C. Finally, the model for the stack emissions is discussed in IV-D.

A. MODEL SCALE

The fully rough flow criterion presented in Eq. (3) of Section II provides a means of selecting the smallest possible model scale. This criterion states that the Reynolds number, $\frac{u_* z_0}{\nu}$, based on the friction velocity, u_* and the characteristic roughness length, z_o , of the ground should be large enough to ensure that the flow will be fully rough. The roughness Reynolds number can be restated in terms of the actual physical height, k , of the roughness elements or the height, k_s , of an equivalent roughness consisting of closely packed sand grains. Reference 13, Equation 20.37 provides the following breakdown of the flow regimes between hydraulically smooth and fully rough flow,

$$\left.\begin{array}{lrcl} \text{hydraulically smooth} & & \dfrac{u_* k_s}{\nu} & < 5 \\ \text{transition} & 5 < & \dfrac{u_* k_s}{\nu} & < 70 \\ \text{completely rough} & & \dfrac{u_* k_s}{\nu} & > 70 \end{array}\right\} \qquad (18)$$

In general, the height of actual roughness elements can be related to an equivalent sand grain roughness height. For the irregular type of ground roughness in the Clairton area, it was estimated that the equivalent sand grain roughness would be about the same as the actual physical height, k_m. That is, in the model, $\frac{u_* k_s}{\nu} \approx \frac{u_* k_m}{\nu}$. Knowing k_m and the kinematic viscosity, ν , it remains to evaluate u_* .

Our experience in calibrating the flow in the ASF has indicated that the ratio $\frac{u_*}{u_{m_{ref}}}$, where $u_{m_{ref}}$ is measured in the free-stream near the ceiling, lies in the range $\frac{u_*}{u_{m_{ref}}} \approx 0.05$. Meteorological wind velocity data are typically measured at a height of 10 meters above ground at a location corresponding to a local maximum ground elevation. The ratio between $u_{m_{ref}}$ and the velocity, $u_{m_{10}}$, at a height in the model corresponding to the full scale measuring station is approximately 2.5. That is $u_{m_{ref}} \approx 2.5\, u_{m_{10}}$. Hence, $u_* \approx 0.125\, u_{m_{10}}$ and the Reynolds number of the roughness elements in the model becomes

$$\frac{u_* k_s}{\nu} \approx \frac{0.125\, u_{m_{10}} \times k_m}{\nu} = 8.6 \times 10^3 u_{m_{10}} k_m \qquad (19)$$

where we have taken $\nu = 1.46 \times 10^{-5}$ meters^2/second, $u_{m_{10}}$ is in meters per second and k_m is in meters.

For geometric scaling between the model and prototype ground roughness, $\frac{k_m}{k_p} = \frac{l_m}{l_p}$, where k_p is the height of the full scale roughness and $\frac{l_m}{l_p}$ is model to prototype scale ratio. For neutrally stable flow, the model velocity u_m is related to full scale conditions by Equation (10). That is

$$\frac{u_m}{u_p} = \sqrt{\frac{\rho_a - \rho_{s_m}}{\rho_a - \rho_{p_m}} \, \frac{l_m}{l_p} \, \sqrt{\frac{\rho_{s_p}}{\rho_{s_m}}}}$$

Preliminary calculations for model stack emissions which would provide proper simulation of the sources listed in the Clairton Model SO_2 Inventory for 1973 indicated that we could use a density defect ratio, $\sqrt{\frac{\rho_{s_p}}{\rho_{s_m}}} \cdot \frac{\rho_a - \rho_{s_m}}{\rho_a - \rho_{s_p}}$, of approximately 1.8. Thus,

$$\frac{u_{m_{10}}}{u_{p_{10}}} = \sqrt{1.8 \, \frac{l_m}{l_p}}$$

Substituting the expressions for $\frac{k_m}{k_p}$ and $\frac{u_{m_{10}}}{u_{p_{10}}}$ in Equation (19), we have

$$\frac{u_* k_s}{\nu} \approx 8.6 \times 10^3 \sqrt{1.8} \left(\frac{l_m}{l_p}\right)^{3/2} u_{p_{10}} k_p \qquad (20)$$

Equation (20) expresses the model ground roughness Reynolds number in terms of the model to prototype scale ratio, the full scale meteorological wind velocity in meters/second, and the full scale terrain roughness height in meters. Inspection of the Clairton area elevation contours on the 1:24,000 U.S. Geological Survey Maps for the Glassport and McKeesport P.A. quadrangles indicated that a value of 91 meters (300 feet) is reasonable for k_p. Using this value, Equation (20) becomes finally

$$\frac{u_* k_s}{\nu} \approx 1.05 \times 10^6 \, u_{p_{10}} \left(\frac{l_m}{l_p}\right)^{3/2} \qquad (21)$$

Equation (21) was used to construct the following table which shows the effect of various scale ratios and full scale winds on the model ground roughness Reynolds number.

TABLE I

Model Ground Roughness Reynolds Number As a Function Of Scale Ratio And Full Scale Wind Speed

Full Scale Wind Speed 10 Meters Above Ground	$\frac{l_m}{l_p} = \frac{1}{1200}$		$\frac{l_m}{l_p} = \frac{1}{2400}$		$\frac{l_m}{l_p} = \frac{1}{3600}$	
$u_{p_{10}}$ m/sec	$\frac{u_* k_s}{\nu}$	$u_{m_{ref}}$ m/sec	$\frac{u_* k_s}{\nu}$	$u_{m_{ref}}$ m/sec	$\frac{u_* k_s}{\nu}$	$u_{m_{ref}}$ m/sec
2	51	0.19	18	0.14	10	0.11
4	101	0.39	36	0.27	19	0.22
6	152	0.48	54	0.41	29	0.34
8	202	0.77	71	0.55	39	0.45
10	253	0.97	89	0.68	49	0.56

The wind tunnel free stream velocity, $u_{m_{ref}}$, has been included in Table I to illustrate how slowly the tunnel must be run in order to obtain proper simulation.

Comparison of the values of $\frac{u_* k_s}{\nu}$ given in Table I with the criteria given by the inequalities (18) shows that for $\frac{l_m}{l_p} = \frac{1}{1200}$, the flow is fully rough over almost the complete wind speed range, for $\frac{l_m}{l_p} = \frac{1}{3600}$, the flow is in the transition regime, and for $\frac{l_m}{l_p} = \frac{1}{2400}$, the higher wind velocities lie in the fully rough regime and the lower wind velocities lie in the transition regime.

There is some question as to how far into the transition region one can go before the model conditions depart significantly from the full-scale conditions. In Appendix A, this matter is discussed in some detail, and it is shown that good modeling probably continues down to a Reynolds number in the neighborhood of 40. Referring again to Table I, it can be seen that, on this basis, at a scale ratio of 1 in 2400 testing could be carried out to equivalent full-scale velocities down to less than 6 m/sec. Therefore, this scale ratio was selected for the model.

B. MODEL CONSTRUCTION

A wooden model was designed and constructed at Calspan based on information supplied by EPA, Region III, Philadelphia, Pennsylvania, H.E. Cramer Company, Inc., and the Allegheny County Health Department. The terrain models were built by photo-enlarging U.S. Geological Survey 1:24,000 scale maps. Three maps were required,

Glassport, Pennsylvania, SW/4 Pittsburgh 15" Quadrangle
McKeesport, Pennsylvania, SE/4 Pittsburgh 15" Quadrangle
Monongahela, Pennsylvania, NW/4 Brownsville 15" Quadrangle

Prints, enlarged to a scale of 1 in 2400, were glued to sheets of plywood which were then cut along contour lines to produce the model as seen in Figure 2, which shows the assembly for the 225° (approximately s-w) wind study. Where the slope of the ground was gradual, 0.63 cm (1/4 inch) sheets of plywood were used corresponding to contour intervals of 15.2 meters (50 feet). Where the ground was steep, 1.27 cm (1/2 inch) sheets of plywood were used corresponding to contour intervals of 30.5 meters (100 feet). The edges of the plywood contour sheets were not smoothed, in order to assist in maintaining the aerodynamically rough wall condition required in the atmospheric boundary layer simulation.

A portion of the terrain model, containing the Clairton complex, was separately mounted on one of the ASF turntables. This circle represented a full-scale diameter of 5.36 kilometers centered at 4462000 m N and 595800 m E on the grid. The amount of terrain modeled upstream and downstream of the turntable varied with wind direction according to the locations of the emission sources and the regions to be studied for SO_2 concentrations. Table II indicates the extent of precise terrain modeling for each wind direction. Figure 4 shows a sketch of the modeled area overlaid on the geological survey maps. Beyond the modeled areas wooden blocks, visible in Figure 2, were distributed to maintain the characteristic roughness length generated in the approaching flow. The latter regions are indicated by dashed lines in Figure 4.

TABLE II

Terrain Modeled in ASF

Wind Direction	Distance Modeled*	
	Upstream	Downstream
225°	14.6 km	5.8
180°	5.8	7.3
331°	5.2	6.4
145°	6.4	5.2

*Distances measured from center of turntable.

Wind angles are refereneced to the northerly grid direction of the 1000 meter Universal Transverse Mercator Grid (UTM), Zone 17. This grid was drawn on the maps used to produce the SO_2 concentration maps. Its northerly direction has been called "REFERENCE NORTH".

Models of the structures and stacks at Mitchell, Elrama, Clairton and Irvin were added to the terrain model. These were made as accurately as possible from the information supplied. The exit diameters of the stacks were held as close as possible to scale size, and a system to supply the stacks with the correct gas mixtures at the correct flow rates was installed below the tunnel. The gas generating system for the stacks has been described in Section III-B.

C. EMISSION INVENTORY AND SOURCE LOCATIONS

A total of 49 stacks were modeled in this study. These stacks comprised the major sources of SO_2 emissions from four locations along the Monongahela River. These are,

(1) Mitchell Power Plant (4 stacks)
(2) Elrama Power Plant (4 stacks)
(3) Clairton Coke Works (33 stacks)
(4) Irvin Works (8 stacks)

The locations of these sources are shown on the terrain map of Figure 4. The full-scale inventory of emissions from these sources is given in Table III. In Figure 4, source locations are indicated by plus signs with numbers adjacent to them. The numbers correspond to the source number listed in Table III. As indicated in Table III, the numbering system for the sources is not consecutive. The numbers correspond to those used by H.E. Cramer Company, Inc.[14] who provided the inventory data.

As illustrated in Figure 4, the Mitchell and Elrama Power Plants and the Irvin Works did not fall within the confines of the turntable in the ASF. Thus, these sources were modeled only for wind directions where they might contribute to the SO_2 concentrations in the Clairton area which was modeled on the ASF turntable. The sources modeled for each of the tested wind directions will be discussed shortly. In all cases, the Clairton Coke Works was modeled. This area contained the majority of the stacks. The locations of the individual stacks in the Coke Works are shown in Figure 5.

D. STACK EMISSION MODEL

As noted above, the 49 stacks listed in Table III were modeled in this study. The Calspan simulation procedure is to use light gases, H_2 and He, for buoyancy, and to make the flux of He proportional to the SO_2 output. The balance of each mixture is made up with N_2. Each sample taken in an experiment is analyzed for He content and the result converted into SO_2 concentration. The flow rates for the various components of the gas mixture for each stack were calculated in accordance with the scaling laws discussed in Section II.

Since the model contained a very large number of stacks (for modeling purposes) with different emission characteristics, the emission scaling calculations become an optimization problem to achieve useful measurement sensitivities. This problem was attacked by setting up a computer program to calculate the H_2, He and N_2 fluxes required to simulate each stack, for various values of $\bar{u}_{am}/\bar{u}_{ap}$ and of $Q^* / \rho^* \phi^*$ (see Section II; Equations (10) and (16)). It is best to keep the velocity ratio the same for all tests for two reasons; first, it makes for better consistency in the approaching boundary-layer flow, and, secondly, it minimizes the number of calibrated gas flows that has to be provided for the series of tests.

TABLE III

1973 Full-Scale SO_2 Emission Inventory[*] Simulated in Model Tests

Source[**]	SO_2 Emission (T/yr)	Stack Height (m)	Temperature (°K)	Volume Flux (m^3/sec)	Stack Radius (m)
1 Clairton Underfire #1	578	69	700	37.27	1.22
2 " " #2	"	"	"	"	"
3 " " #3	"	"	"	"	"
7 " " #7	"	65	"	35.87	1.27
8 " " #8	"	"	"	"	"
9 " " #9	"	"	"	"	"
10 " " #10	"	69	"	37.27	1.22
11 " " #11	"	"	"	"	"
12 " " #12	"	"	"	"	"
13 " " #13	"	"	"	37.74	1.31
14 " " #14	"	"	"	"	"
15 " " #15	"	"	"	"	"
16 " " #16	"	61	"	32.13	"
17 " " #17	"	"	"	"	"
18 " " #18	"	76	"	32.30	1.46
19 " " #19	"	"	"	58.43	2.14
20 " " #20	"	"	"	"	"
21 " " #21	"	"	"	"	"
22 " " #22	"	"	"	"	"
23 " " #12A	"	69	"	35.87	1.52
24 Clairton B & W #1	3,730	50	455	92.57	1.37
25 Clairton CE #2	1,175	"	"	72.33	1.06
26 Clairton Benzene Boiler	588	53	616	36.55	0.99
27 " " "	"	"	"	"	"
28 Clairton Blast Furnance	303	60	716	180.58	1.88
30 Clairton Claus Plant	5,074	58	561	18.03	0.61
31 Irvin 3 & 4	824	53	646	54.55	1.79

TABLE III (Cont'd)

	Source[**]	SO_2 Emission (T/yr)	Stack Height (m)	Temperature (°K)	Volume Flux (m^3/sec)	Stack Radius (m)
32	Irvin 5 & 6	1,232	75	633	79.62	1.60
33	Irvin 7	937	27	483	33.40	0.92
35	Elrama	12,079	65	416	198.95	2.15
36	"	"	"	430	"	"
37	"	13,920	"	"	229.45	"
38	"	20,935	89	416	299.14	2.30
39	Mitchell	27,142	82	403	534.81	3.05
40	"	6,769	70	467	223.64	2.15
41	"	"	"	"	"	"
42	"	"	"	"	"	"
43	Irvin Reheat	365	21	700	89.57	1.23
44	" "	"	"	"	"	"
45	" "	"	"	"	"	"
46	" "	"	"	"	"	"
47	" "	"	"	"	"	"
48	Clairton Reheat	131	31	811	27.50	0.65
49	" "	"	"	"	"	"
50	" "	"	"	"	"	"
51	" "	"	"	"	"	"
52	" "	"	26	"	"	"
53	" "	"	"	"	"	"
54	" "	"	"	"	"	"

[*] Data supplied by H.E. Cramer Company, Inc.

[**] Source numbering system is not consecutive. It corresponds to system used in Reference 14. With this system, numbers 3, 4, 5, 6, 29, and 34 are omitted.

Using the computer program, it was established that it would not be possible to simulate the complete inventory at one time and maintain reasonable sensitivity. This situation arises because the source inventory (Table III) contains stacks where the highest outputs of SO_2 in general occur with relatively low temperatures, and vice-versa. Hence, the program was broken down into four parts, each with one group of stacks fully simulated. The separate parts will be described shortly.

The computer program quickly showed when a particular choice of parameters was unsuitable, by indicating negative fluxes of one gas component. A suitable choice of the parameter η (Equation 11), used in conjunction with Equation (10) to calculate model stack density, was

$$\eta = 1.8 \tag{22}$$

This value was used throughout. The stack exit velocities, and hence volume fluxes, were calculated from Equation (6).

The amount of He used in each fully-simulated stack was set by the choice of a parameter defined as

$$\lambda = \frac{\text{Flux of } SO_2 \text{ (Tons/year in Full Scale)}}{\text{Flux of He (cm}^3\text{/min.)}} \tag{23}$$

This can be converted to the quantity $Q^* / \rho^* \phi^*$ used in Equation (16). The concentration ratio between full-scale SO_2 and model He becomes

$$\frac{C_p}{C_m} = 3.01 \times 10^{-6} \lambda \tag{24}$$

where C_p = ppm SO_2 in full scale
C_m = ppm He measured in model tests.

Equation (24) holds for the complete model study. The parameter λ was varied for the four different groups of stacks. The four groups of stacks for which different values of λ were used are as follows,

(1) Mitchell
(2) Elrama
(3) Clairton (excluding Claus) and Irvin
(4) Claus (Claus Plant is source number 30 in Table III and Figure 5)

When testing for dispersion of SO_2 from Mitchell, Elrama, or Claus, interaction effects between the plumes from these sources and the plumes from the Clairton Works were simulated even though the Clairton Works were not under study for SO_2 dispersion. This was done by equipping the Clairton complex, including the Claus plant, with two gas-supply arrangements, one in which He was included to simulate the SO_2 emissions, and one in which He was excluded but the correct exit momenta and buoyancies were maintained so that dynamic coupling between plumes would be retained when the SO_2 emissions were not being simulated.

The division of the emission modeling into four groups of stacks required that separate tests be performed to obtain concentration measurements for the complete inventory of stacks. Thus, for a given wind condition (direction, velocity and stability) each stack group was operated separately and ground level helium concentrations were measured downstream. The separate results were then converted to full scale SO_2 concentrations and added to obtain the SO_2 concentrations for the complete inventory. Table IV lists the various combinations of stack groups used for each wind direction. The second column in Table IV lists the stack group under test for helium concentration levels and the third column lists the stack group which was operated without helium to allow for plume interaction effects. The fourth column lists the parameter λ (Equation (23)) used for each test group and the fifth column shows the scaling factor between the measured He concentration levels and the full-scale SO_2 concentration levels.

The last column in Table IV provides an estimate of the resolution of the gas sampling system at low levels in terms of full scale SO_2 concentration. The values in this column are based on calibrations of the model gas sampling system when a true concentration of 10 ppm He is inserted into the sampling system. The spread in the calibration data was approximately ±5 ppm He under

TABLE IV

Stack Emission Groups And Scale Factors Used In Model Concentration Level Tests

Wind Direction (See Figure 3)	Source Group Simulated Dynamically And For SO_2	Source Group Simulated Dynamically Only	λ (Equation 23)	Emission Scale Factor, Cp/Cm (Equation 24)	Possible Error* in Full Scale SO_2 at Low Concentration Levels
225°	Mitchell	Clairton and Claus	323	0.97×10^{-3}	± 0.005 ppm
225°	Elrama	Clairton and Claus	410	1.23×10^{-3}	± 0.006 ppm
225°	Claus	Clairton	1000	3.01×10^{-3}	± 0.015 ppm
225°	Clairton	Claus	200	0.60×10^{-3}	± 0.003 ppm
180°	Claus	Clairton	1000	3.01×10^{-3}	± 0.015 ppm
180°	Clairton	Claus	200	0.60×10^{-3}	± 0.003 ppm
145°	Claus	Clairton	1000	3.01×10^{-3}	± 0.015 ppm
145°	Clairton	Claus	200	0.60×10^{-3}	± 0.003 ppm
331°	Claus	Clairton and Irvin	1000	3.01×10^{-3}	± 0.015 ppm
331°	Clairton and Irvin	Claus	200	0.60×10^{-3}	± 0.003 ppm

*Calculated possible error at low concentration levels is based on calibrated resolution of ±5 ppm He in model gas sampling system. Calibration at high concentration levels indicated an accuracy better than ±10 percent.

these conditions. At high concentration levels, the calibrations indicated an accuracy better than ±10 percent. Typical calibrations for the various channels of the sampling system are given in Figure 6. As noted in Section III-B, our objective in this study was to maintain a resolution of ±0.01 ppm in full-scale SO_2 concentration levels. As indicated in column 6 of Table IV, this objective was attained for all stack groups except the Claus Plant where it is estimated at ±0.015 ppm SO_2. The Claus Plant (Source number 30 in Table III) is a particularly difficult modeling situation because it has high SO_2 emissions combined with moderately low temperature and very low volume flux. The low temperature and volume flux limits the amount of He that can be used if correct scaling is to be preserved.

All of the stack groups listed in Table IV were tested at three reference wind velocities. In addition, the tests were repeated at one of the reference wind velocities with the LN_2 generated temperature inversion. This made a total of forty tests to determine concentration levels. Thus, the procedure of separating the complete emission inventory into separate groups for testing required an extensive amount of concentration testing. However, one advantage of the procedure adopted is that it allows assessment of the individual contributions from the various stack groups to the overall ground level concentrations of SO_2.

V. DESCRIPTION OF THE TEST PROCEDURES

The appropriate portions of the terrain model were installed in the ASF and wooden-block rough-floor sections were used to fill in the upstream and downstream portions of the tunnel. In Figure 2, which is a view looking upwind with the configuration of the 225° (sw) wind series of tests, most of the details can be seen. Starting in the far distance, the 30 cm-high trip fence is clearly visible. This is followed by a predominantly white region which is the wooden-block rough floor. The slightly darker bands of unpainted blocks are at the locations where liquid nitrogen (LN_2) is poured onto the tunnel floor to create an inversion. These sections consist of metal plates with a pattern of blocks laid out to encourage uniform distribution of the LN_2 which is delivered to the roof of the tunnel by a distribution system terminating in four sintered-metal phase separators which pour smooth streams of LN_2 through holes in the tunnel ceiling and down onto the metal plates.

The terrain model is the black contoured area, with the Elrama, and Clairton complexes plainly visible. The Mitchell Power Plant is beneath the right hand of the man in the background. Intruding from the right is the thermistor rake mounted on the traverse mechanism, with an attachment point for a heat-pulse anemometer. These instruments were used to obtain inversion temperature profiles and velocity profiles.

The tunnel speed was set at a reference height of 4 feet (1.22 meters) above the model river. This corresponds to 2,926 meters in full-scale. A smoke-puff generator was installed at this height and the time of passage between two axial locations measured with a stop-watch. The three reference velocities used, were

$u_{m_{ref}}$ = 0.22, 0.41, and 0.60 meters/sec in the model tests, or
$u_{p_{ref}}$ = 8, 15, and 22 meters/sec expressed in terms of full-scale values.

The full-scale values are accurate to approximately ±1 m/sec. Reference velocities at other heights can be obtained through the velocity profiles, which are discussed later.

The model inventory of effluents was set up by adjusting the flow rates through suitable stainless steel capillary tubes with lengths of piano wire inserted in them. Each capillary was calibrated by measuring the volume of water displaced from a graduated glass cylinder in a measured time interval. The back pressure on the capillary was at most a few centimeters of water, whereas the supply pressure was 598 cm H_2O above ambient (8.5 psig). Thus, the calibration technique was accurate to better than 1% in most cases. Only for some of the very small flows, where it became difficult to read the graduated cylinder with sufficient accuracy, did the calibration accuracy deteriorate. However, these small flows contribute little to the overall result. Each capillary was adjusted by trimming the inserted wire until the flow rate was within 10% of the required rate in all but the lowest flow cases. The Helium flow rates, which have a very direct bearing on the results, were set up as far as possible to considerably better than ±10% accuracy.

Smoke visualization was used to assist in locating appropriate sampling points for the first two series of tests. The smoke was generated by inserting test tubes containing a small amount of Titanium Tetrachloride just below the tunnel floor and passing the stack gas supplied through these test tubes.

The gas sampling system, which is described in Section III-B, was connected via long plastic tubes to the sampling points on the model. The method utilized through this program to bring the sample gases to the capillaries in the sampling system was as follows. A multiport plenum was held at a pressure of 12.7 cm H_2O below ambient by a simple jet pump driven by compressed N_2. Small diameter plastic tubes were strung from the sampling points on the model to the ports of the jet-pump plenum. At each port where a plastic tube was connected, a specially adapted Tee fitting was used which held the end of a sampling capillary very close to, and coaxial with, the tube to which the plastic line was attached. The slight gap between them was thus exposed to the jet-pump plenum suction in such a way that the capillary opening was fully immersed in the flow of its particular sample mixture.

The lengths of plastic tubing required to reach between the model sampling locations and the gas sampling system were quite long in some cases. This made it important to know the maximum total time delay between the sampling location on the model and appearance of the sample in its holding chamber in the system. This total delay was determined by testing to be less than 30 seconds with the plastic tubing contributing less than 18 seconds to the total. Thus, throughout the program, the stacks and the jet pump were turned on 45 seconds before measurements commenced to provide a generous margin of safety in flushing time.

As discussed in Section II-C, the averaging time for making measurements in the ASF is not directly related to the averaging time in full-scale. The latter has an effect on the result arising from meandering of the wind which is not duplicated in the model tests. The choice of averaging time in the model study is simply a matter of repeatability, so that to some accuracy the results can be expected to be consistent. Equation (17) of Section II-C was used to estimate the averaging time required for 10 percent accuracy in these tests. For the reference velocities used, the results are

Full Scale reference velocity, $u_{p_{ref}}$ = 8, 15, 22 m/sec
Model reference velocity, $u_{m_{ref}}$ = 0.22, 0.41, 0.60 m/sec
Model sampling time for 10% accuracy, t_s = 454, 244, 167 sec

As noted in Section II-C, Equation (17) is only approximate. Usually in practice, these estimates are conservative. It was found that the gas sampling system could be made to work well with sampling times up to 300 seconds. Thus, a 300 second averaging time was adopted for all of the measurements.

Finally, a comment should be made regarding the upstream reference sample, which critically affects the data at very low concentration levels. During the course of a day's operation the background helium level in the laboratory rises slightly. In these tests, the amount of helium used was quite small and the laboratory is a very large building. Nevertheless, the resolution required was such that the background level of helium had to be known accurately. It was realized early in the program that the LN_2 used to create the inversion contained less helium than normal air. Since the gas in contact with the model was predominantly N_2 which had evaporated from the LN_2 poured on the floor upstream, the background He concentration was lower than in the ambient air.

Thus, during the neutral stability tests the background He concentration was simply that of the ambient air in the laboratory and the position of the upstream reference sample was immaterial. When the temperature-inversion system was operating, however, it was necessary to use a ground-level sample upstream in order to obtain a true background reading. It did not appear that the ambient air penetrated significantly to ground level as the flow passed over the model during the inversion runs. Except for the first few neutral stability tests, a ground-level upstream reference was used throughout.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results are presented in three parts. The flow conditions over the model are presented in VI-A. Flow visualization studies are discussed in VI-B. Finally, the ground level concentration measurements are presented in VI-C.

A. MODEL ATMOSPHERIC WIND CONDITIONS

1. Approaching Flow

The problem of selecting a model scale for the extensive area required for this study has been discussed in Section IV-A. In that section, a scale of 1:2400 was selected on the basis of the estimated ground roughness Reynolds number attainable. With the scale selected, it is possible to obtain a more accurate evaluation of this Reynolds number in the flow development region upstream of the model.

The approaching flow was developed over a random distribution of wooden blocks with a mean height of 3.81 cm, equivalent to 91.4 meters in full scale. This random roughness height provided a good match for the mean height of the model terrain. Moreover, the flow over the random roughness elements had been calibrated through extensive measurements with hot-wire anemometers. The calibration measurements provided the following results for the approaching flow;

Ground Roughness Length, z_o = 0.12 cm

Ratio of Friction Velocity to Reference Velocity, $\frac{u_{*m}}{u_{m_{ref}}} = 0.052$

Thus, the ground roughness Reynolds number is

$$\frac{u_{*m} z_{om}}{\nu} = \frac{z_{om} \frac{u_{*m}}{u_{m_{ref}}} u_{m_{ref}}}{\nu}$$

$$= 4.27\, u_{m_{ref}} \quad \text{where} \quad \nu = 1.46 \times 10^{-5} \text{ meters}^2/\text{sec}$$

The model ground roughness Reynolds number at the velocities selected for the tests become:

Full-Scale reference velocity, $u_{p_{ref}}$ = 8, 15, 22 m/sec
Model reference velocity, $u_{m_{ref}}$ = 0.22, 0.41, 0.60 m/sec
Model ground roughness Reynolds No., $\frac{u_{*m} z_{om}}{\nu}$ = 0.94, 1.75, 2.56

These Reynolds numbers are shown in Figure 7 on a graph which illustrates the effect of lowering the Reynolds number below the recommended value of approximately 3 (Equation (3) in Section II). Such effects have been discussed in Reference 13; Figure 7 has been prepared from the experimental data given there in a fashion similar to that discussed in Appendix A. The dashed lines in Figure 7 enclose the scatter of experimental data presented in Reference 13.

Figure 7 shows that as the Reynolds number is lowered from a value of about 3, the effective roughness length increases at first. The Reynolds numbers for the three velocities used in the tests (indicated by arrows), fall at the beginning of the increase of effective roughness length. Only the highest velocity, $u_{p_{ref}}$ = 22 m/sec, is within the range for completely rough flow. The intermediate velocity ($u_{p_{ref}}$ = 15 m/sec) provided a Reynolds number where the effective roughness length has just begun to increase. The mean deviation from completely rough conditions is about 6 percent in terms of effective roughness length. This deviation is within the accuracy of determining roughness lengths from measurements and is thus considered to be acceptable. The lowest reference velocity used can be seen to be definitely in the transition Reynolds number range, with an effective roughness length about 20 percent greater than that for fully rough flow. Thus, the lowest test velocity was probably too low to provide the proper model flow.

2. Flow Over the Model

Velocity and temperature profiles in the flow over the model were measured at four locations for the configuration used with a 225 degree wind direction. This configuration had the most extensive amount of model terrain and the largest number of stacks (see Figure 4). The heat-pulse anemometer and thermistor rake were used to make the velocity and temperature measurements. The measurement locations were as follows:

(1) Above the Mitchell Power Plant
(2) Above the Elrama Power Plant
(3) Above the approximate middle of the Clairton Coke Works
(4) Above the Liberty Borough School Monitoring Station

The mean velocity profiles at each location are shown in Figures 8 through 11 and the temperature profiles in the LN_2 generated model inversion are shown in Figures 12 through 15. All measurements were made with a model reference velocity, $u_{m_{ref}}$ = 0.41 m/sec corresponding to $u_{p_{ref}}$ = 15m/sec in full scale. The data are presented in terms of equivalent full-scale values. The velocity profiles are estimated to be accurate to within better than 10 percent of the true value. The accuracy with which the temperature profiles were determined corresponds to about ±1/2°C in terms of full scale. The latter accuracy was governed by the ability to average turbulence generated temperature fluctuations displayed on the chart recordings of the thermistor outputs.

The velocity profiles in Figures 8 through 11 are presented for neutral stability and for the model inversion. The data for the Mitchell Power Plant shows an additional velocity profile (dashed line labeled High-Speed Calibration Profile in Figure 8). This profile was measured over the random wooden block ground during tunnel calibration. Conventional hot-wire anemometry was used to obtain this profile. The reference velocity was much higher than those used herein, $u_{m_{ref}}$ = 13 m/sec. providing a ground roughness Reynolds number, $\frac{u_{*m} z_{o_m}}{\nu} \approx 55$, well above the transition range shown in Figure 7. This same ground was used to develop the flow approaching the model. For the 225 degree wind direction, it ended just upstream of the Mitchell Power Plant (see Figure 4) so the neutral stability profile at Mitchell should agree reasonably well with the calibration profile. As can be seen in Figure 8, the agreement between the low-speed ($u_{m_{ref}}$ = 0.41 m/sec) neutral stability profile and the high-speed ($u_{m_{ref}}$ = 13 m/sec) calibration profile is remarkably good. These profiles can, therefore, be assumed to hold for all except the lowest reference speed used in the tests. The heat-pulse anemometer used to obtain the low-speed velocity data did not read below about 0.15 m/sec. Hence, we could not check the velocity profile corresponding to a full-scale reference velocity of 8 m/sec which is only 0.21 m/sec in the model.

Inspection of the neutral stability velocity profiles in Figures 8 through 11 shows that the presence of the Monongahela River valley causes a distortion in the velocity profiles. The degree of distortion can be seen by comparison of the neutral stability profiles for Elrama, Clairton, and Liberty Borough with that for Mitchell. The Mitchell profile has been added to Figures 9, 10 and 11 to facilitate the comparison. The Elrama profile shows a small amount of distortion close to the river valley. The small differences at high altitudes are within the probable measurement accuracy. At Clairton, the velocity profile is distorted below about 300 meters. The distortion is most pronounced at the Liberty Borough School which is in the wake of the steep bluffs on the North-East side of the river near the Clairton Coke Works (see Figures 4 and 5). This wake apparently reaches an altitude of about 1300 meters at the Liberty Borough School. The profile for Liberty Borough is shown as a dotted line below 400 meters because the heat-pulse anemometer readings are questionable at the apparent low velocities encountered in this region.

The velocity profiles measured at the various locations above the model in the presence of the LN_2 generated temperature inversion are shown as solid points in Figures 8 through 11. The velocities measured with the temperature inversion are, in general, considerably higher than those measured for neutral stability and the shapes of the profiles are different for the the two cases. The higher velocities associated with the temperature inversion will have an effect on the ground level concentration data presented later, since the velocities at stack (and plume) heights are affected. Thus, the inversion SO_2 data measured with a full scale reference velocity, $u_{p_{ref}}$ = 15 m/sec, will tend to compare with the neutral atmosphere data taken with $u_{p_{ref}}$ = 22 m/sec.

The temperature profiles in Figures 12 through 15 show that the inversion over the model began at Mitchell approximately as a ground level inversion with a gradient of 3.2°C per 100 meters. Then, since the model itself was not cooled, the inversion became elevated with an unstable layer beneath it close to the ground. The elevated inversion persisted as far as the Liberty Borough

School with a maximum temperature gradient of approximately 1.9°C per 100 meters.at a full-scale heights between 300 and 500 meters above the river level. In all cases, the heights where the maximum temperature gradients were observed corresponded closely to the heights where the maximum velocity gradients were observed.

One of the problems encountered in interpreting model test data, or for that matter full scale data, is the selection of a location for measuring the mean wind velocity. In full scale these are usually measured at meteorological stations which may be remote from the area of interest. Moreover, the anemometers are located at low altitudes, typically 10 meters above local ground level. The measured wind velocities can be influenced by the local terrain in a fashion similar to that apparent in the neutral stability profile for the Liberty Borough School (Figure 11). In the ASF, the possibility of local terrain influences on the reference wind velocity is avoided by selecting a measuring location well above the terrain, in this case at an effective full scale height of 2926 meters above the river bed. However, this reference velocity is still required to have a known relationship with some full-scale meteorological station. In the current program, the continuous monitoring station at Liberty Borough School provides a satisfactory reference location since it is located within the confines of the modeled area. The neutral stability velocity profile at this location (Figure 11) indicates that the velocity near ground level is approximately 0.4 times the reference velocity at 2926 meters. Thus, for example, a full scale reference velocity of 15 meters per second is equivalent to approximately 6 meters per second measured at the Liberty Borough School. Similarly, with the temperature inversion, the above factor becomes 0.6 and a 15 m/sec reference velocity corresponds to approximately 9 m/sec at Liberty Borough.

Velocity profiles were measure only for the 225 degree wind direction. However, the data measured at Elrama and Clairton (Figures 9 and 10) suggest that the velocities near ground level are relatively insensitive to the local terrain. Thus, wind direction should not greatly influence the relationship between the reference velocity and the velocity at the Liberty

Borough School. Therefore, the relations discussed in the previous paragraph will be used for all four of the wind directions studied. Both the reference wind velocity and the approximate velocity at Liberty Borough School will be noted in the presentation of the ground level concentration data.

B. FLOW VISUALIZATION

As mentioned in Section V, smoke flow visualization was used to assist in locating appropriate sampling points for the first two series of tests with wind directions of 225 degrees and 180 degrees. Some photographs of these tests are shown in Figures 16 and 17 for the 225 degree wind direction. The Clairton Coke Works, with many of the stacks carrying $TiCl_4$ to produce smoke, is shown in Figure 16(a) under neutral stability conditions and in Figure 16(b) under inversion conditions. The main stack of the Mitchell power plant is shown operating under neutral stability conditions in Figure 17(a), and the main stack of the Elrama power plant under inversion conditions in Figure 17(b).

At the model scale of 1:2400, it was very difficult to generate the smoke emissions for any length of time because deposits of TiO_2 tended to accumulate rapidly on humid days and either completely block the small stacks or change the effective stack geometry. Thus, a great deal of time was spent in cleaning out deposits before each test. An attempt to minimize the formation of TiO_2 deposits was made by using a concentric tube design for the largest stacks on the Mitchell and Elrama power plants. The emission gas mixture was divided and $TiCl_4$ vapor was introduced only to that portion of the gas that went through the central tube. The dry emission gas in the outer tube shielded the $TiCl_4$ vapor from atmospheric moisture until it had exited from the stack. This arrangement worked fairly well as evidenced in Figure 17. However, it could not be used on smaller stacks because of their size.

The small size of the model stacks and the low flow rates required for proper scaling of the buoyant plumes generated a laminar flow within the stacks. In full scale these stack flows are generally turbulent. In the immediate vicinity of the stack exit, plume dispersion with turbulent emissions is more rapid than it is with laminar emissions. The small plume dispersion with the laminar model emissions is evident in Figures 17(a) and (b) very close to the stack exits. Farther from the stack exit, plume dispersion becomes dominated by atmospheric turbulence. The latter region is also evident in Figure 17. In general, the plume rise of an initially laminar plume will exceed that of an initially turbulent plume because the turbulent plume mixes more rapidly with the ambient air. However, the initial plume rise observed in these tests with laminar stack emissions was quite small before atmospheric turbulence began to dominate the mixing process. For example, at the Clairton Coke Works (Figure 16) and at the Mitchell powerplant (Figure 17(a)) atmospheric turbulence began to dominate the mixing process before the plumes had completely crossed the model river valley. Thus, except for the ground level regions close to the stacks, the quantitative concentration level measurements should scale properly if the model sampling time is long enough to compensate for the lack of initial turbulent diffusion near the stack exits. This point is discussed further in Section VI-C.

It was shown in Section VI-A that the minimum wind speed used in this study ($u'_{p\,ref}$ = 8 m/sec) was probably too low to provide the proper model flow for the atmospheric wind. The flow visualization studies tended to confirm this in a qualitative way. The smoke plumes from the stacks showed an intermittent behaviour at the lowest test velocity. At times, the plumes rose to substantial heights and at other times the plumes acted approximately as they did at the higher test velocities. This behaviour was particularly noticeable at the Mitchell power plant where the approaching flow has the least distance for development downstream of the fence. Thus, it is concluded, on the basis of the Reynolds number calculations in Section VI-A and the smoke visualization observations, that the lowest test speed did not provide proper modeling of the atmsopheric wind. The ground level concentrations which were obtained at this lowest test velocity are not included in the presentation of the experimental results. However, these data are listed in the tables in Appendix B for those who are interested.

C. GROUND LEVEL CONCENTRATIONS

1. Preliminary Near Field Test

In the discussion of the flow visualization tests, it was noted that the model flow leaving the stacks was laminar rather than turbulent. Dispersion of these laminar plumes is not as rapid as that of full-scale turbulent plumes. The flow visualization showed that plume dispersion became dominated by atmospheric turbulence a short distance from the stack exits. Thus, the model plume concentration levels should provide representative full-scale values at moderate to large distances from the stacks. However, the lack of initial model plume dispersion will affect the ground level concentration measurements close to the stacks, even for distances where atmospheric turbulence has begun to dominate the mixing process. In this region, a long time sample of the concentration at a point will provide approximately correct values but shorter time samples will deviate from the correct value because the lack of initial turbulent diffusion accentuates the timewise intermittency in the local concentration levels. The estimates in Section V for the sampling time required in the model tests do not allow for this intermittency. Hence, for sampling points very close to a source, we might expect that the maximum error in the measurements may exceed the 10 percent value estimated in Section V for a sampling time of 300 seconds.

The possible error in the measurements close to a source can be evaluated by comparing the results of separate test runs taken under identical operating conditions. Table V shows the results obtained on two successive days with the model of the Mitchell power station operating with a neutrally stable atmosphere. The model reference velocity $u_{m_{ref}}$ was 0.60 m/sec (equivalent to 22 m/sec in full scale) and the wind direction was 225 degrees for these tests.

The location of the sampling points listed in Column 1 of Table V can be seen in Figures 18, 19 and 20. (These figures will be discussed shortly.) Approximate full-scale distances downwind of Mitchell are listed in Column 2.

TABLE V

Comparison of Ground Level Concentrations Measured in Separate Tests for Identical Operating Conditions: Mitchell Power Plant Model, Neutral Atmosphere, 225° Wind Direction, Full-Scale Reference Velocity, $U_{p_{ref}} = 22$ m/sec

Sampling Point Number (See Figs. 18 to 20)	Approximate Distance Downwind of Source (Km, full-scale)	Full-Scale SO_2 Concentration Level (ppm) Calculated From Model Test Data		Deviation From Average	
		Test No. 1	Test No. 2	ppm SO_2	%
1	0.3	0.577	0.409	0.084	17.0
2	0.8	0.183	0.074	0.055	42.4
3	0.8	0.525	0.436	0.045	9.3
4	0.8	0.441	0.433	0.004	*
5	1.5	0.021	0.006	0.008	*
6	1.5	0.253	0.213	0.020	8.6
7	1.5	0.199	0.195	0.002	*
8	3.2	0.057	0.033	0.012	26.7
9	4.2	0.066	0.074	0.004	*
11	6.4	0.042	0.036	0.003	*
12	6.8	0.008	0.004	0.002	*
15	8.1	0.025	0.018	0.004	*
21	10.4	0.018	0.007	0.006	*

* Within resolution of approximately 0.01 ppm SO_2

Sampling point number 1 is at river level directly downwind of Mitchell. The next three points are near the top of the escarpment with sampling point number 2 close to one edge of the plume. The remaining points are at increasing distances downwind. Columns 3 and 4 in Table V list the ground level concentrations in terms of ppm SO_2 in full scale and Column 5 shows the deviation in these data from the average value. The deviations are presented in terms of ppm SO_2 and also in terms of percent for those values which exceed a resolution of 0.01 ppm SO_2.

As noted previously, our objective in these tests was to maintain a resolution of approximately ±0.01 ppm SO_2 or an accuracy of ±10 percent (whichever was larger). While the data in Table V show that it is possible to find results which exceed these limits close to a source, they also show very good consistency a short distance downwind. Only sampling point numbers 1, 2 and 8 exceed the above limits and the deviation in sampling points 1 and 2 is expected. Sampling point number 8, which is further downstream, shows a deviation of 0.012 ppm from the average. This is a negligible amount greater than the desired resolution. Thus, Table V indicates that except for sampling locations very close to a source, the desired accuracy was attained. The fact that a lesser accuracy may be attained at the first one or two sampling points closest to a source should be borne in mind when using the data in this report.

2. SO_2 Concentrations

The ground level concentration data are presented in tabular form in Appendix B. These data were used to prepare isopleths of the full-scale ground level SO_2 concentrations. As explained in Section IV-D, the tests were performed with various combinations of stacks operating at different times. (The various stack groups which were studied have been listed in Table IV.) Thus, it is possible to identify the individual contributions from each stack group to the overall ground level concentrations. This has been done for some of the stack groups. Selected individual results and the overall results corresponding to operation of all stacks are presented in Figures 18 through 39. Table VI is an index to these figures.

TABLE VI

Index to Figures Presenting Ground Level SO_2 Concentrations

Figure Number	Wind Direction (deg)	Full-Scale Reference Wind Velocity (m/sec.)	Source Group					
			Mitchell	Elrama	Clairton & Claus	Claus Alone	Mitchell, Elrama, Clairton, & Claus	Clairton, Claus, & Irvin
18	225	15	X					
19	225	22	X					
20	225	15 (Inversion)	X					
21	225	15		X				
22	225	22		X				
23	225	15 (Inversion)		X				
24	225	15			X			
25	225	22			X			
26	225	15 (Inversion)			X			
27	225	15					X	
28	225	22					X	
29	225	15 (Inversion)					X	
30	180	15			X			
31	180	22			X			
32	180	15 (Inversion)			X			
33	180	15				X		
34	145	15			X			
35	145	22			X			
36	145	15 (Inversion)			X			
37	331	15						X
38	331	22						X
39	331	15 (Inversion)						X

The data in Figures 18 through 39 are presented in terms of full-scale ground level concentrations of SO_2. On each figure, sampling point locations are denoted by plus signs with an adjacent flag.* The circled number in the flag indicates the number assigned to the sampling point and the uncircled number is the full-scale concentration of SO_2 in ppm. The full-scale SO_2 concentrations were calculated from the measured helium concentrations in the manner explained in Section IV-D. With the 225 degree wind direction (Figures 18 through 29) a total of 41 sampling point locations were used with the various stack groups. Each of these locations was assigned a permanent number. However, only 20 locations could be accommodated by the gas sampling system at one time. The 20 locations selected for use with each stack group in Figures 18 through 29 are indicated by the flags which contain SO_2 concentration data.

Isopleths of SO_2 concentration levels have been drawn as solid lines through the data in the figures. The SO_2 concentration levels for the isopleths are indicated at breaks in the solid lines. For the majority of Figures 18 through 39, the sampling point locations used with the various source groups were coincident, so the overall SO_2 concentrations could be obtained by adding the contributions of SO_2 from each source group. However, for the 225 degree wind direction, many of the sampling point locations used with the Mitchell and Elrama source groups were not coincident with each other or with those used with the Clairton and Claus source groups. Thus, to obtain the total SO_2 concentration levels from all of these source groups (shown in Figures 27, 28 and 29), isopleths were drawn through the available data for the Mitchell and the Elrama source groups, as in Figures 18 through 23, and the isopleths were then combined with the Clairton and Claus data (Figures 24 through 26).

Although the program reported herein was intended primarily as a data gathering study, there are some features in the data which are worthy of specific comment. However, before proceeding to these comments, it is appropriate to point out what trends one might expect in the data.

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*The source locations for Mitchell, Elrama, Claus and Irvin are indicated in these figures when appropriate. The locations of the remaining sources within the Clairton Works are shown in Figure 5.

In general, we expect to find that the effect of increasing the wind speed will be to increase the immediate downwind SO_2 concentrations because the plumes are increasingly held down. Farther downwind, increasing wind speed should decrease the far field SO_2 concentrations because of stretching out of the plume gases in the wind direction. The presence of an inversion will generally tend to hold the plumes down and increase the SO_2 concentrations both near the source and in the far field for a given wind velocity. These general effects may be modified considerably in the present case by the very rough terrain in the area of interest and the presence of the Monongahela River Valley with its steep bluffs. The valley and bluffs may tend to steer the local wind and to promote plume downwash near the sources. Such effects can be seen in some of the SO_2 concentration data which are discussed in the following paragraphs under sub-headings which identify the sources simulated and the wind direction.

225 Degree Wind; Mitchell Simulated (Figures 18, 19 and 20)

The classic effects with changing wind speed are evident in Figures 18 and 19 for neutrally stable flow. Increasing the wind speed increases the local SO_2 concentrations and decreases the far field concentrations. There is some evidence at the higher wind speed (Figure 19) of local steering of the flow by the river valley. The isopleths in the near field appear to be deflected to the left of the prevailing wind direction. Moreover, the SO_2 concentration level at sampling point number 1, which is at river level, is comparable in magnitude to the maximum values observed near the top of the bluff (sampling point numbers 3 and 4). This suggests that there is a considerable downwash effect which is caused by the presence of the relatively steep bluffs near the Mitchell Power Plant. The model bluffs near Mitchell can be seen in Figure 17(a). At the lower wind speed (Figure 18) neither the flow steering or downwash effects are as apparent.

The effect of the inversion (Figure 19) is difficult to separate from the effect of changes in wind speed. As discussed in Section VI A.2, the velocity profiles measured with the inversion indicated that the velocity at stack and plume height was increased when the inversion was generated. It was suggested in that discussion that the inversion data should be compared with the neutral atmosphere data taken at a reference velocity $u_{p_{ref.}} = 22$ m/sec. If this is done, then the measured velocities at plume height with and without the inversion are approximately equal. For example, the velocities at the Liberty Burough School become 8.8 m/sec in the neutral atmosphere (Figure 19) and 9 m/sec with the inversion (Figure 20).

A comparison of the data in Figures 19 and 20 shows that the inversion had only a small effect on the near field concentration levels. Steering of the flow by the river valley is not evident in the inversion data but there is still a large downwash into the river valley at sampling point number 1. Moreover, the concentration observed on the bluffs immediately downwind of Mitchell are comparable in both cases. In the far field, the inversion increased the observed concentration levels by a factor of approximately two in the Clairton area.

In general, the far field data for the Mitchell Power Plant show a very slight tendency towards deflection of the isopleths around the bend in the river at the Clairton Coke Works. However, the number of sampling points in this region was limited, so the slight steering of the plume indicated by the isopleths may not be real.

225 Degree Wind; Elrama Simulated (Figures 21, 22 and 23)

For neutrally stable flow (Figures 21 and 22), the effects of changing wind speed on the ground level SO_2 concentrations are not as consistent as they were with Mitchell. In the near field, the ground level concentrations increase as expected with increasing wind speed. However, the far field data remain at levels as high as or higher than those observed at the lower wind speed. In addition, the higher speed data (Figure 22) show greater lateral diffusion to the left after the bend in the river at Clairton. Apparently, the higher wind velocity holds the plume down enough that the bluffs near Clairton can deflect some of it to the left.

The most apparent effect of the inversion (Figure 23) is to increase the SO_2 concentration levels observed in the far field. In the near field, the plume does not appear to reach ground as close to Elrama as it did for neutral flow at either wind velocity. The presence of the river bend has no apparent effect in this case.

225 Degree Wind; Clairton (Including Claus) Simulated (Figures 24, 24 and 26)

The ground level SO_2 concentrations for this case arise as a result of a highly complex combination of multiple stacks in the presence of steep bluffs perpendicular to the wind direction. The model terrain near the sources can be seen in Figure 16 and the distribution of the 33 sources is shown in Figure 5. In the model emission inventory (Table III) the single largest contribution of SO_2 comes from the Claus Plant (source number 30). The location of this source is identified separately in the SO_2 concentration figures. Two other sources have higher than average SO_2 emissions. These are source numbers 24 and 25 in Figure 5. In Figures 24 through 29 these two sources are located near the river bank directly below the circled number 30. Sampling point numbers 24, 26, 30, 32, 33 and 40 are at river level. The remainder are at considerably higher elevations which are listed in Appendix B.

Inspection of Figures 24, 25 and 26 shows that there is considerable downwash of the plumes in all these cases. The SO_2 values at river level just downwind of the Claus Plant (sampling point number 26) are comparable to, or larger than, those observed on the bluffs (sampling point numbers 25, 27 and 28). The highest values occur at the lowest wind speed, which is to be expected since downwash occurred at all of the tested wind velocities. Even the data at the lowest wind velocity ($u_{P_{ref}}$ = 8 m/sec), which are not presented in the figures because the ground roughness Reynolds number was too low, indicated a very large downwash just downstream of the Claus Plant.

The near field concentration isopleths in Figures 24, 25 and 26 show evidence of the contribution from source numbers 24 and 25 as well as from the Claus Plant. This is most noticeable in Figures 25 and 26 where locally high concentration levels can be seen near sampling point number 31.

In the far field, the SO_2 concentrations decrease with increasing wind speed in the usual fashion. The inversion (Figure 26) had an unusual effect in this case. The far field concentration levels decrease in comparison with either of the neutrally stable flow tests and the plume trajectory is deflected slightly to the left. The low concentration levels with the inversion are probably the result of increased wind velocities downwind of the river. Velocity profiles above the Liberty Borough School (Figure 11) show a rapid increase in velocity with height between about 450 and 550 meters. This is the same region where the temperature gradient is a maximum (Figure 15). If portions of the plume from the Clairton area are deflected upwards by the river bluff to heights above 400 meters, then these portions will be above the elevated inversion layer and will be swept away rapidly by the high wind velocity.

225 Degree Wind; Mitchell, Elrama, Clairton (Including Claus) Simulated (Figures 27, 28 and 29)

In these figures, the far field SO_2 concentration isopleths from the Mitchell and Elrama plumes have been added to the isopleths from the Clairton Coke Works. The wind direction for this series of tests was such that the plumes from Mitchell and Elrama were almost directly in line with each other. The composite plume from these two sources contributes almost all of the SO_2 to the isopleths to the right of sampling point number 41.

For the particular wind direction used in this test series, the Glassport monitor was completely bypassed by the plumes from the various sources and the Liberty Borough monitor just picked up the left edge of the composite plume. However, a small decrease in wind angle would place the Liberty Borough monitor within the plumes from Clairton and Mitchell and a slightly larger decrease would bring in the Elrama plume. If it is assumed that the isopleths do not change shape rapidly with small changes in wind angle, then one can rotate the isopleths from each source group about the source to obtain the SO_2 levels at Liberty Borough for slightly different wind directions. For example, if this procedure is used for a neutral wind at a velocity of 6 m/sec at the Liberty Borough monitor (Figures 18, 21 and 24) and the Claus Plant is used as the center of rotation for the data in Figure 24, then one obtains SO_2 concentration levels at Liberty Borough of approximately 0.08 to 0.09 ppm SO_2 for wind angles between 200 and 218 degrees.

The above result compares quite favorably with full-scale data measured at Liberty Borough on 18 January 1973. During hours 13 and 14 (EST) on that date, the wind speed was relatively steady between 6.2 and 6.7 m/sec, the wind angle was close to 220 degrees, and the atmospheric stability was neutral (see Tables 6-5 and 6-7 of Reference 14). The full scale SO_2 concentrations measured at Liberty Borough under these conditions were between 0.115 and 0.13 ppm SO_2.

180 Degree Wind; Clairton (Including Claus) Simulated (Figures 30, 31 and 32)

The results shown in these figures are similar to those obtained with this source group at a wind direction of 225 degrees. There is evidence of plume downwash at sampling point numbers 6 and 8 which are at river level. The effects of contributions from the Claus Plant and from source numbers 24 and 25 are apparent in the kidney shaped isopleths. In this case also, the wind direction was such as to place the Glassport and Liberty Borough monitoring stations on the edges of the plume so that neither monitor location received much SO_2. Of course, a small change in wind direction should place one or the other of the monitoring stations within the plume. For example, rotating the isopleths in Figure 30 about the Claus Plant indicates that about 0.07 ppm SO_2 would be measured at Liberty Borough for a wind angle of 200 degrees. This agrees well with the value 0.08 ppm, obtained by rotating the isopleths in Figure 24 to the same wind angle.

There is some question that SO_2 levels at the Glassport monitoring station can be estimated easily for wind angles other than those tested. This monitor is near river level and the SO_2 levels may be influenced by local flows around the river bluffs. The data obtained for a wind direction of 145 degrees, which are presented below, show evidence of such influence.

180 Degree Wind; Claus Plant Simulated (Figure 33)

This figure is included to show the contribution of the Claus Plant to the ground level SO_2 concentrations from the Clairton Coke Works. The results can be compared to those in Figure 30, which shows the SO_2 isopleths for all of the Clairton Coke Works, including the Claus Plant.

145 Degree Wind; Clairton (Including Claus) Simulated (Figures 34, 35 and 36)

The wind direction used in this test series was chosen because it placed the Glassport monitoring station directly downwind of the majority of sources in the Clairton Coke Works. Thus, if the plumes were not much affected by the presence of the river valley and bluffs, the Glassport monitor should be centered approximately in the composite plume. We understand that this particular monitoring station has consistently provided SO_2 concentration levels which are lower than expected for wind directions near 145 degrees. The model test data in Figures 34, 35 and 36 provide an illustration of how the low readings arise.

In all three cases, shown in Figures 34, 35 and 36, the ground level isopleths deflect around the right side of the Glassport monitor. This monitor is close to the river level, so one might speculate that the composite plume is lifted over the monitor. However, sampling point numbers 12 and 19 are also near river level, upwind and downwind of the Glassport monitor. These sampling points detected significant quantities of SO_2. Moreover, the upwind river-level sampling point (number 12), detected the highest SO_2 levels measured anywhere in the area. Thus, it appears that the composite plume reaches ground well before the Glassport monitor, but that the plume is locally deflected to the right by flow disturbances from bluffs on the sides of the river valley. The direction in which the local flow is deflected is rather surprising since the river valley angles slightly to the left near the Glassport monitor.

331 Degree Wind; Clairton (Including Claus) and Irvin Simulated (Figures 37, 38 and 39)

The final wind direction studied in this test program was chosen to place the Irvin Works directly upwind of the Clairton Coke Works. With this configuration, the Glassport monitor lies approximately midway between the source groups.

For neutral flow (Figures 37 and 38), wind speed has a large effect on the ground level data. At the lowest velocity (Figure 37), the plumes apparently rise quite high and the SO_2 levels are low everywhere except directly downwind of the Claus Plant, at sampling point number 16. At this sampling point, the separate tests with the Claus Plant simulated by itself showed that the total SO_2 concentration level (0.08 ppm) is composed of 0.06 ppm from the Claus Plant and 0.02 ppm from all the remaining sources. The Glassport monitor shows no detectable SO_2 at this low wind speed. For the higher wind speed (Figure 38), the SO_2 levels increase everywhere near the river valley. The plume from Irvin appears to reach ground in the vicinity of the Glassport monitor and relatively high SO_2 levels are detected there. Concentration levels of SO_2 downwind of the Clairton Coke Works also increase significantly at the higher wind speed. At sampling point number 16, the SO_2 contribution from the Claus Plant decreased to 0.04 ppm while that from the remaining sources increased to 0.14 ppm.

With the inversion (Figure 39), the SO_2 levels downstream of Irvin are low and comparable in magnitude to those observed in neutral flow at the lower wind speed (Figure 37). However, the isopleths are deflected to the left, along the river valley, during the inversion. Downstream of the Clairton Coke Works, the isopleths are again deflected to the left by the inversion. Sampling point numbers 13, 15 and 18, which are to the left of the Clairton Coke Works, show significant increases in SO_2 level with the inversion. All of the SO_2 at these sampling points came from sources other than the Claus Plant. At sampling point number 16, the relative contributions from the Claus Plant and from the remaining sources are 0.04 and 0.07 ppm SO_2 respectively.

3. Summary

In the preceding paragraphs, the model test results have been discussed with a view toward identifying unusual dispersion patterns caused by the presence of the Monongahela River Valley with its steep bluffs. Ground-level concentration data were presented in terms of full-scale SO_2 concentration levels for four wind directions, two wind speeds in neutrally stable flow, and one wind speed with an inversion.

The results indicate that the river valley and bluffs do have an effect on the dispersion patterns. The largest effects were observed on the plumes from the Clairton Coke Works. For South and South-West wind directions, the plumes from the Coke Works appear to be deflected down into the river valley at the base of the bluffs. Concentration levels comparable to or higher than those observed near the top of the bluffs were obtained at the base. For a wind direction of 145 degrees, the isopleths of the ground level SO_2 show an unusual deflection around the Glassport monitoring station, missing this monitor almost completely. In the absence of local flow disturbances from the bluffs, the Glassport monitor would lie near the center of the plumes for this wind direction.

The effect of the inversion used in these model tests was inconsistent. The inversion appeared to hold down the plumes from Elrama and Mitchell, increasing the far-field SO_2 levels over those observed with neutral flow for comparable wind velocities at the Liberty Borough School. This is the expected result. However, with the Clairton Coke Works as the source of emissions, the far field SO_2 levels sometimes decreased with the inversion

(225° wind direction), sometimes remained almost unchanged (180° wind direction) and sometimes the whole isopleth pattern changed shape (331° wind direction). The inconsistent effects of the inversion on the plumes from the Clairton Coke Works are probably a result of flow disturbances caused by the steep bluffs.

For all except one test, the model results showed very low SO_2 concentration levels at the locations of the Liberty Borough and Glassport monitoring stations. In the one exception, the Glassport monitor detected relatively high concentration levels downwind of the Irvin Works (331° wind direction). The low observed levels at Liberty Borough appear to be a result of the choice of wind directions for the test program. Other wind directions would probably have placed this monitor within the plumes. However, the same general comment does not appear to apply to the Glassport monitor. This monitor was almost completely bypassed by the composite plume from the Clairton Coke Works when it should have been situated in the middle of this plume (145° wind direction). Thus, the Glassport monitor appears to be located in an area where local flow disturbances from the bluffs are critical in determining the detected SO_2 levels. We understand this result is consistent with full-scale observations where the Glassport monitor has been detecting lower SO_2 levels than expected under similar circumstances.

Finally, an indirect comparison between the model test results and full-scale measurements of SO_2 concentration levels at the Liberty Borough monitor has been made for one wind condition. Full-scale hourly concentrations between 0.115 and 0.13 ppm SO_2 were measured on 18 January 1973, during a relatively steady wind with a velocity between 6.2 and 6.7 m/sec, a direction close to 220 degrees, and conditions of neutral stability. The model test results obtained with neutral flow at a wind direction of 225 degrees were used to estimate SO_2 levels at the Liberty Borough monitor for wind directions near 220 degrees and a velocity of 6 m/sec at Liberty Borough. The estimates based on the model test results indicated approximately constant SO_2 concentration levels of 0.08 to 0.09 ppm for wind directions between 200 and 218 degrees. This compares favorably with the full-scale values noted above.

VII. CONCLUDING REMARKS

The model study reported here was a formidable undertaking in many respects. The large number of stacks to be modeled (49), each with its own emission characteristics, made the design and fabrication of the stack gas generating system highly complex. In addition, the extent of model terrain required a model-to-prototype scale ratio (1:2400) which was much smaller than that usually used. This, in turn, required careful consideration of the model scaling laws and led to some compromises to the final design.

Because of the small scale of the model, it was not possible to obtain turbulent flow within the model stacks. The plumes leaving the stacks were initially laminar. As such, the model plumes may have risen higher very close to the stacks than the corresponding turbulent plumes from the full-scale stacks. However, smoke visualization of the model plumes showed that plume dispersion rapidly became dominated by atmospheric turbulence a short distance from the stacks. Moreover, ground level concentration measurements showed evidence of considerable downwash close to the stacks in most tests, presumably because of the very rough terrain and the river valley. This suggests that the initially laminar flow at the stack exits did not have a large effect on the results.

In addition to the presence of laminar flow in the model stacks, the small scale of the model and the large extent of terrain modeled limited the range of wind speeds and directions which could be tested during this program. The necessity for extensive modeling of the terrain upstream and downstream of the turntable in the ASF made it impractical to perform tests for more than a few wind angles, since each wind angle required its own model terrain. The small scale of the model limited the wind speeds which could be simulated properly to values above about 6 m/sec measured in full-scale at the Liberty Borough School.

One series of tests was performed for a smaller wind speed, but the ground roughness Reynolds number corresponding to this speed was too small for proper flow simulation. The minimum wind speed limit would have been even higher if the full-scale terrain in the area had not been very rough, with hills and valleys about 90 meters in depth.

One of the aims of this study was to investigate the effects of an inversion on ground level SO_2 concentrations. To do this required the development of a system for generating an inversion in the ASF. A liquid nitrogen distribution system for generating an inversion was developed and tested as a part of this program. The results are reported in the text.

The purpose of this model testing program was to provide data on the ground level concentrations of SO_2 generated by the various sources in the area. The main body of the results is presented in terms of full-scale ground level SO_2 concentrations for the various test conditions.

The discussion of the results is oriented towards identifying situations where the local terrain appears to modify normal plume dispersion patterns. In general, it was found that the presence of the river valley with its steep bluffs did have local effects on the plume dispersion. The concentration data indicated the presence of considerable downwash near the face of the bluffs in the area near the Clairton Coke Works and to a lesser extent near the Mitchell Power Plant. In addition, there is evidence that the river valley and bluffs can deflect the plumes to a certain extent. The most unusual plume deflection observed, occurred for a wind direction which was chosen to place the Glassport monitoring station directly downwind and in the center of the composite plume from sources in the Clairton Coke Works. The test results showed that the plume was deflected around the Glassport station, missing it almost completely.

The effect of the model inversion on the ground level concentrations can be described as inconsistent. The inversion had the expected effect on the plumes from the Mitchell and Elrama Power Plants, increasing the measured concentrations in the far field. However, the effect of the inversion on the plumes from the Clairton Coke Works appeared to depend on the wind direction, sometimes increasing ground level concentrations and sometimes decreasing them. These effects are discussed in the main body of the text.

In conclusion, it is clear from the data presented that the terrain does influence dispersion of the plumes. It is believed such influence would be impossible to predict without model tests or extensive full-scale measurements.

APPENDIX A

MINIMUM PERMISSIBLE GROUND ROUGHNESS REYNOLDS NUMBER

In many cases of modeling atmospheric flows in a wind tunnel, it is not practical to satisfy completely the fully rough flow boundary conditions for the flow over the model under all wind conditions. It is then of interest to estimate how small the roughness Reynolds number can be before significant deviations occur from the ideal flow. One approach to this problem is presented briefly in the following paragraphs.

The mean velocity profile near the ground can be expressed as (Ref. 13, Eq. 20-32)

$$\frac{u}{u_*} = 2.5 \ln\left(\frac{z}{k_s}\right) + B = 5.75 \log\left(\frac{z}{k_s}\right) + B \qquad \text{(A-1)}$$

where B = a constant

k_s = the height of closely packed sand grain roughness

u = mean velocity at height z

u_* = friction velocity

z = vertical height above ground

Equation (A-1) can be rewritten in terms of a characteristic roughness length z_o as follows

$$\frac{u}{u_*} = 5.75 \log \frac{z}{z_o} \qquad \text{(A-2)}$$

where we have used the relation

$$\frac{k_s}{z_o} = \log^{-1}\left(\frac{B}{5.75}\right) \qquad \text{(A-3)}$$

For fully rough flow B = 8.5, making $\frac{k_s}{z_o}$ = 30.1

To plot $\frac{k_s}{z_0}$ as a function of the roughness Reynolds number, we can use Figure 20:21 of Reference 13, which is a plot of B vs $\frac{u_* k_s}{\nu}$, substituting for B from Equation (A-3). The result is shown in Figure 40.

It can be seen that $\frac{k_s}{z_0}$ increases gradually in the transition zone as $\frac{u_* k_s}{\nu}$ is decreased below a value of 70. For $\frac{u_* k_s}{\nu} = 40$, the mean value of $\frac{k_s}{z_0}$ is about fifteen percent above its value in the completely rough regime. In practice, it is difficult to determine values of z_0 over a given roughness to much greater accuracy than plus or minus ten percent, even with very careful measurements and an independent determination of u_*, for example from the Reynold s stress profile. In many field evaluations of z_0, both u_* and z_0 are estimated from measured mean velocity profiles. That is, u_* is not determined independently. In these cases, it is unlikely that calculated values of z_0 approach the accuracy mentioned above. Thus, it appears consistent with the general accuracy of the modeling to allow testing down to model roughness Reynolds number of forty. This is equivalent to a value of about 1.3 if the Reynolds number is based on z_0 rather than k_s.

APPENDIX B

TABLE OF GROUND LEVEL SO_2 CONCENTRATIONS CALCULATED FROM MODEL TEST DATA

Ground level SO_2 concentrations calculated from the model test results are listed in the following tables. In each table, Column 1 identifies the sampling point by an assigned number. The locations of the sampling points are shown in the figures identified in brackets below the Column 1 title. Column 2 shows the local ground elevation above river level for each sampling point. The remaining columns list the SO_2 concentration levels obtained with the various source groups operating. In columns identified as totals in the title, SO_2 levels were obtained by adding contributions from the appropriate individual source groups. Apparent negative SO_2 concentration levels listed in the tables were all smaller than the resolution of the concentration measuring equipment. These small negative values were taken as zero when adding contributions to obtain total SO_2 concentration levels.

With the 225 degree wind direction, the twenty sampling channels available in the testing equipment were not sufficient to provide a good distribution of sampling point locations for all four source groups. Accordingly, a total of 41 sampling point locations were used in these tests, but only 20 of these were used with any one source group. Thus, it was necessary to interpolate the measured data to obtain the totals for all 41 sampling locations. This was done by drawing isopleths through the available data for each source group to estimate the SO_2 levels at the missing locations. Data estimated in this way are shown in brackets in the columns for the individual source groups. All of the data calculated from direct measurements are given to three decimal places. Data estimated by interpolation from the isopleths and also total concentrations obtained by addition are listed to two decimal places.

All of the data measured during the course of the test program are listed in the tables, including data taken at the lowest wind speed which was too low for proper modeling. The latter are listed for the sake of completeness and are identified in the title of the table as taken in the absence of proper simulation.

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
(Data listed on this page were measured at a wind speed too low for proper modeling)
Wind Direction: 225°
Wind Velocity: Full Scale - 8 m/sec @ 2926 meters above river level
Model - 0.22 m/sec @ 1.22 meters above river level

Sampling Point No. (See Figs 18-29)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm) Mitchell	Elrama	Claus Plant	Clairton Excluding Claus	Total All Sources
1	0	.056	U	U	U	.06
2	85	.009	U	U	U	.01
3	85	.032	U	U	U	.03
4	55	.008	U	U	U	.01
5	85	.009	U	U	U	.01
6	85	.048	U	U	U	.05
7	55	.015	U	U	U	.02
8	0	.068	U	U	U	.07
9	55	.057	U	U	U	.06
10	0	( )	.017	U	U	
11	24	.107	.002	U	U	.11
12	0	.060	.020	U	U	.08
13	0	( )	.016	U	U	
14	24	( )	.019	U	U	
15	0	.107	.018	U	U	.13
16	55	( )	.002	U	U	
17	24	( )	.013	U	U	
18	0	( )	.029	U	U	
19	0	( )	.021	U	U	
20	116	( )	0	U	U	
21	0	.092	.021	U	U	.11
22	55	( )	.039	U	U	
23	146	.061	.047	0	.001	.11
24	0	.111	.008	.001	.001	.12
25	116	.090	.004	.018	.156	.27
26	0	( )	( )	.694	.124	
27	55	( )	( )	.340	.080	
28	116	( )	( )	.180	.080	
29	85	( )	( )	-.001	.056	
30	0	( )	( )	.002	.051	
31	85	( )	( )	.001	.037	
32 *	0	-.001	0	.001	0	0
33	0	.004	-.001	.002	.055	.06
34	158	( )	( )	.001	.005	
35	116	( )	( )	.028	.076	
36	85	( )	( )	.003	.066	
37 **	85	.000	-.001	0	.008	.01
38	55	( )	( )	.003	.033	
39	55	( )	( )	.001	.028	
40	0	( )	( )	.016	.038	
41	85	.060	.040	.002	.023	.13
42	116	( )	( )	0	.010	

* Glassport Sampler
**Liberty Borough Sampler

Note: 1. SO_2 concentrations in brackets are estimated from isopleths based on the available measured data.
2. U designates sampling points are upwind of the source and thus will not contribute to the total SO_2 level.

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 225°
Wind Velocity: Full Scale - 15 m/sec @ 2926 meters above river level,
6 m/sec @ Liberty Borough School
Model - 0.41 m/sec @ 1.22 meters above river level,
0.16 m/sec @ Liberty Borough School

Sampling Point No. (See Figs 18-29)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)					
		Mitchell (Fig 18)	Elrama (Fig 21)	Claus Plant	Clairton Excluding Claus	Total Clairton & Claus (Fig. 24)	Total All Sources
1	0	.134	U	U	U	U	0.13
2	85	.039	U	U	U	U	0.04
3	85	.255	U	U	U	U	0.26
4	55	.097	U	U	U	U	0.10
5	85	.008	U	U	U	U	0.01
6	85	.192	U	U	U	U	19
7	55	.060	U	U	U	U	06
8	0	.045	U	U	U	U	.05
9	55	.078	U	U	U	U	.08
10	0	(.05)	.146	U	U	U	.20
11	24	031	0	U	U	U	03
12	0	.015	.194	U	U	U	.21
13	0	(.05)	.095	U	U	U	.15
14	24	(.02)	.120	U	U	U	.14
15	0	.069	.058	U	U	U	.13
16	55	(.04)	.001	U	U	U	.04
17	24	(.01)	.053	U	U	U	.06
18	0	(.05)	.094	U	U	U	.14
19	0	(.06)	.044	U	U	U	.10
20	116	(.02)	0	U	U	U	.02
21	0	.050	.038	U	U	U	.09
22	55	(.03)	.051	U	U	U	.08
23	146	.015	.034	0	.002	0	.08
24	0	.060	.004	.002	.003	.01	.07
25	116	.034	0	.025	.121	.15	.18
26	0	(.02)	(0)	.480	.106	.59	.61
27	55	(.01)	(0)	.312	.111	.42	.43
28	116	(.01)	(0)	.167	.105	.27	.28
29	85	(.01)	(0)	.003	.092	.10	.11
30	0	(0)	(0)	0	.091	.09	.09
31	85	(0)	(0)	-.001	.044	.04	.04
32 *	0	0	0	.001	.001	0	0
33	0	.002	0	.001	.107	.11	.11
34	158	(.05)	(.01)	-.002	.006	.01	.07
35	116	(.03)	(0)	.019	.059	.08	.11
36	85	(.01)	(0)	-.001	.074	.07	.08
37 **	85	0	0	0	.004	0	0
38	55	(.05)	(0)	.001	.027	.03	.08
39	55	(0)	(0)	-.004	.033	.03	.03
40	0	(.02)	(0)	.020	.039	.06	.08
41	85	.052	.006	.002	.013	.02	.07
42	116	(0)	(0)	0	.007	.01	.01

* Glassport Sampler
** Liberty Borough Sampler

Note: 1. SO_2 Concentrations in brackets are estimated from isopleths based on the available measured data
2. U designates sampling points are upwind of the source and thus will not contribute to the total SO_2 level.

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 225°
Wind Velocity: Full Scale - 22 m/sec @ 2926 meters above river level,
8.8 m/sc @ Liberty Borough School
Model - 0.60 m/sec @ 1.22 meters above river level,
0.24 m/sec @ Liberty Borough School

Sampling Point No. (See Figs 18-29)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm) Mitchell (Fig. 19)	Elrama (Fig 22)	Claus Plant	Clairton Excluding Claus	Total Clairton & Claus (Fig 25)	Total All Sources (Fig 28)
1	0	.409	U	U	U	U	.41
2	85	.074	U	U	U	U	.07
3	85	.436	U	U	U	U	.44
4	55	.433	U	U	U	U	.44
5	85	.006	U	U	U	U	.01
6	85	.213	U	U	U	U	.21
7	55	.195	U	U	U	U	.20
8	0	.033	U	U	U	U	.03
9	55	.074	U	U	U	U	.07
10	0	(.04)	.557	U	U	U	.60
11	24	.036	0	U	U	U	.04
12	0	.004	.269	U	U	U	.27
13	0	(.03)	.323	U	U	U	.35
14	24	(0)	.139	U	U	U	.14
15	0	.018	.149	U	U	U	.17
16	55	(.02)	.066	U	U	U	.03
17	24	(0)	.041	U	U	U	.04
18	0	(0)	.113	U	U	U	.11
19	0	(.02)	.091	U	U	U	.11
20	116	(.02)	.002	U	U	U	.02
21	0	.007	.072	U	U	U	.08
22	55	(0)	.041	U	U	U	.04
23	146	.007	.038	-.002	.002	0	.05
24	0	.017	.032	.001	.009	.01	.05
25	116	.017	.007	.008	.067	.08	.10
26	0	(.02)	(.01)	.151	.074	.23	.26
27	55	(.01)	(.01)	.134	.081	.21	.23
28	116	(.01)	(.01)	.088	.072	.16	.18
29	85	(0)	(.01)	.005	.078	.08	.09
30	0	(0)	(0)	.002	.044	.05	.05
31	85	(0)	(0)	.001	.087	.09	.09
32 *	0	0	(0)	.001	.001	0	0
33	0	.003	.006	0	.060	.06	.07
34	158	(.02)	(.02)	.001	.005	.01	.05
35	116	(.02)	(.02)	.009	.031	.04	.08
36	85	0	(.01)	.003	.045	.05	.06
37 **	85	.001	.005	-.002	.011	.01	.02
38	55	(.01)	(.02)	.001	.009	.01	.04
39	55	(0)	(.01)	.001	.032	.03	.04
40	0	(.01)	(.02)	.009	.018	.03	.06
41	85	.013	.016	0	.004	0	.03
42	116	(0)	(.01)	0	.010	.01	.02

* Glassport Sampler
**Liberty Borough Sampler

Note:
1. SO_2 concentrations in brackets are estimated from isopleths based on the available measured data.
2. U designates sampling points are upwind of the source and thus will not contribute to the total SO_2 level.

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 225° (with inversion)
Wind Velocity: Full Scale - 15 m/sec A 2926 meters above river level,
9 m/sec @ Liberty Borough School
Model - 0.41 m/sec @ 1.22 meters above river level,
0.25 m/sec @ Liberty Borough School

Sampling Point No. (See Figs 18-29)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)					
		Mitchell (Fig 20)	Elrama (Fig 23)	Claus Plant	Clairton Excluding Claus	Total Clairton & Claus (Fig 26)	Total All Sources (Fig 29)
1	0	.461	U	U	U	U	.46
2	85	.125	U	U	U	U	.13
3	85	.463	U	U	U	U	.46
4	55	.199	U	U	U	U	.20
5	85	.020	U	U	U	U	.02
6	85	.235	U	U	U	U	.24
7	55	.060	U	U	U	U	.06
8	0	.068	U	U	U	U	.07
9	55	.050	U	U	U	U	.05
10	0	(.07)	.083	U	U	U	.15
11	24	.068	-.001	U	U	U	.07
12	0	.050	.278	U	U	U	.33
13	0	(.07)	.068	U	U	U	.14
14	24	(.04)	.195	U	U	U	.24
15	0	.065	.059	U	U	U	.12
16	55	(.04)	.001	U	U	U	.04
17	24	(.02)	.167	U	U	U	.19
18	0	(.05)	.137	U	U	U	.19
19	0	(.05)	.054	U	U	U	.11
20	116	(.03)	0	U	U	U	.03
21	0	.050	.065	U	U	U	.12
22	55	(.03)	.102	U	U	U	.13
23	146	.042	.065	-.001	.002	0	.11
24	0	.043	.019	0	.006	.01	.07
25	116	.034	.005	.002	.046	.05	.09
26	0	(.03)	(0)	.089	.055	.14	.17
27	55	(.02)	(0)	.102	.057	.16	.18
28	116	(.02)	(0)	.064	.046	.11	.13
29	85	(.01)	(0)	.009	.079	.09	.10
30	0	(.01)	(0)	.001	.042	.04	.05
31	85	(.01)	(0)	.001	.103	.10	.11
32 *	0	0	0	0	0	0	0
33	0	.007	0	.001	.043	.04	.05
34	158	(.04)	(.03)	.001	.003	0	.07
35	116	(.03)	(.01)	.003	.013	.02	.06
36	85	(.01)	(0)	.009	.036	.05	.06
37 **	85	.004	0	0	.019	.02	.02
38	55	(.03)	(.02)	.001	.002	0	.05
39	55	(.01)	(0)	.004	.022	.03	.04
40	0	(.02)	(.01)	.004	.007	.01	.04
41	85	.032	.020	.002	.002	0	.06
42	116	0	(0)	.003	.015	.02	.02

* Glassport Sampler
** Liberty Borough Sampler

Note: 1. SO_2 concentrations in brackets are estimated from isopleths based on the available measured data.
2. U designates sampling points are upwind of the source and, thus will not contribute to the total SO_2 level.

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
(Data listed on this page were measured at a wind speed too low for proper modeling.)
Wind Direction- 180°
Wind Velocity: Full Scale - 8 m/sec @ 2926 meters above river level
Model - 0.22 m/sec @ 1.22 meters above river level

Sampling Point No. (See Figs 30-33)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant	Clairton Excluding Claus	Total Clairton & Claus
1	0	.005	.006	.01
2	116	0	0	0
3	85	.020	.009	.03
4	116	.001	.001	0
5	85	.072	.016	.09
6	0	.007	.044	.05
7	85	0	.064	.06
8	0	0	.001	0
9	85	0	0	0
10	85	.009	.006	.02
11	134	0	.025	.03
12	55	0	.002	0
13 *	0	.001	.002	0
14	55	0	0	0
15 **	85	0	.003	0
16	134	.002	.014	.02
17	116	-.001	.002	0
18	0	.001	.001	0
19	0	-.001	.004	0
20	116	-.001	.004	0

* Glassport Sampler
**Liberty Borough Sampler

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 180°
Wind Velocity: Full Scale - 15 m/sec @ 2926 meters above river level,
6 m/sec @ Liberty Borough School
Model - 0.41 m/sec @ 1.22 meters above river level,
0.16 m/sec @ Liberty Borough School

Sampling Point No. (See Figs 30-33)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant (Fig 33)	Clairton Excluding Claus	Total Clairton & Claus (Fig 30)
1	0	.004	.022	.02
2	116	.002	.001	0
3	85	.002	.028	.03
4	116	.001	.009	.01
5	85	.068	.079	.15
6	0	.136	.109	.25
7	85	.026	.093	.12
8	0	.002	.155	.16
9	85	.002	.002	0
10	85	.032	.038	.07
11	134	.009	.062	.07
12	55	.002	.104	.11
13 *	0	.002	.003	.01
14	55	.001	.001	0
15 **	85	.001	.004	.01
16	134	.027	.041	.07
17	116	.001	.044	.05
18	0	.002	.001	0
19	0	.004	.021	.03
20	116	.002	.017	.02

* Glassport Sampler
** Liberty Borough Sampler

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 180°
Wind Velocity: Full Scale - 22 m/sec @ 2926 meters above river level,
8.8 m/sec @ Liberty Borough School
Model - 0.60 m/sec @ 1.22 meters above river level,
0.24 m/sec @ Liberty Borough School

Sampling Point No. (See Figs 30-33)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm) Claus Plant	Clairton Excluding Claus	Total Clairton & Claus (Fig 31)
1	0	.002	.018	.02
2	116	-.002	.001	0
3	85	-.003	.024	.02
4	116	-.003	.007	.01
5	85	.032	.050	.08
6	0	.095	.068	.16
7	85	.025	.060	.09
8	0	.002	.136	.14
9	85	-.003	.001	0
10	85	.021	.029	.05
11	134	.009	.038	.05
12	55	.001	.020	.02
13 *	0	.005	.001	.01
14	55	-.002	0	0
15 **	85	-.002	.003	0
16	134	.023	.025	.05
17	116	.010	.027	.04
18	0	.025	.005	.03
19	0	.006	.010	.02
20	116	.003	.008	.01

* Glassport Sampler
** Liberty Borough Sampler

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 180° (with inversion)
Wind Velocity: Full Scale - 15 m/sec @ 2926 meters above river level,
9 m/sec @ Liberty Borough School
Model - 0.41 m/sec @ 1.22 meters above river level,
0.25 m/sec @ Liberty Borough School

Sampling Point No. (See Fig 30-33)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant	Clairton Excluding Claus	Total Clairton & Claus (Fig 32)
1	0	.002	.046	.05
2	116	.001	.003	0
3	85	.001	.050	.05
4	116	0	.023	.02
5	85	.087	.071	.16
6	0	.057	.076	.13
7	85	.010	.075	.09
8	0	.002	.217	.22
9	85	.002	.008	.01
10	85	.032	.035	.07
11	134	.005	.039	.04
12	55	0	.090	.09
13*	0	.002	.012	.01
14	55	.001	.002	0
15**	85	.015	.012	.03
16	134	.013	.026	.04
17	116	.001	.034	.04
18	0	.001	.010	.01
19	0	.003	.011	.01
20	116	.002	.010	.01

* Glassport Sampler
**Liberty Borough Sampler

Full-Scale Ground Level Concentration of SO_2 Calculated from Model Test Data
(Data listed on this page were measured at a wind speed too low for proper modeling.)

Wind Direction: 145°

Wind Velocity: Full Scale - 8 m/sec @ 2926 meters above river level
Model - 0.22 m/sec @ 1.22 meters above river level

Sampling Point No (See Fig 34-36)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm) Claus Plant	Clairton Excluding Claus	Total Clairton & Claus
1	55	.005	.001	.01
2	55	.002	0	0
3	55	.002	0	0
4	0	.005	.001	.01
5	0	.006	.005	.01
6	24	.003	.001	0
7	85	.004	.002	.01
8	0	.009	.010	.02
9	55	.001	0	0
10	85	.004	.008	.01
11**	85	.002	0	0
12	0	.080	.011	.09
13	24	.001	.001	0
14	55	.015	.008	.02
15*	0	0	0	0
16	55	.002	.001	0
17	116	.011	.003	.01
18	55	.021	.009	.03
19	0	.021	.009	.03
20	55	.004	.005	.01

* Glassport Sampler

** Liberty Borough Sampler

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 145°
Wind Velocity: Full Scale - 15 m/sec @ 2926 meters above river level,
6 m/sec @ Liberty Borough School
Model - 0.41 m/sec @ 1.22 meters above river level,
0.16 m/sec @ Liberty Borough School

Sampling Point No (See Fig 34-36)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant	Clairton Excluding Claus	Total Clairton & Claus (Fig 34)
1	55	.003	.001	0
2	55	0	0	0
3	55	.001	.001	0
4	0	.001	.001	0
5	0	.001	.003	0
6	24	.001	.003	0
7	85	.001	.005	.01
8	0	.005	.023	.03
9	55	0	0	0
10	85	.017	.030	.05
11 **	85	0	0	0
12	0	.031	.204	.23
13	24	-.002	.001	0
14	55	.029	.068	.10
15 *	0	-.001	.001	0
16	55	.001	.001	0
17	116	.001	.001	0
18	55	0	.004	0
19	0	.006	.035	.04
20	55	.011	.038	.04

* Glassport Sampler
** Liberty Borough Sampler

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 145°
Wind Velocity: Full Scale - 22 m/sec @ 2926 meters above river level,
8.8 m/sec @ Liberty Borough School
Model - 0.60 m/sec @ 1.22 meters above river level,
0.24 m/sec @ Liberty Borough School

Sampling Point No (see Fig 34-36)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant	Clairton Excluding Claus	Total Clairton & Claus (Fig 35)
1	55	.004	.010	.01
2	55	.001	.001	0
3	55	.002	.005	.01
4	0	.005	.002	.01
5	0	.006	.002	.01
6	24	.003	.003	.01
7	85	.005	.002	.01
8	0	.018	.020	.04
9	55	.001	.001	0
10	85	.006	.016	.02
11**	85	.004	.004	.01
12	0	.077	.120	.20
13	24	.001	.002	0
14	55	.022	.032	.05
15*	0	.011	.001	.01
16	55	.004	.002	.01
17	116	.014	.004	.02
18	55	.013	.053	.07
19	0	.035	.039	.07
20	55	.007	.014	.02

* Glassport Sampler
**Liberty Borough Sampler

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 145° (with inversion)
Wind Velocity: Full Scale - 15 m/sec @ 2926 meters above river level,
9 m/sec @ Liberty Borough School
Model - 0.41 m/sec @ 1.22 meters above river level,
0.25 m/sec @ Liberty Borough School

Sampling Point No. (see Fig 34-36)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant	Clairton Excluding Claus	Total Clairton & Claus (Fig 36)
1	55	.002	.011	.01
2	55	.002	.003	0
3	55	.002	.001	0
4	0	.003	.011	.01
5	0	.002	0	0
6	24	.001	.001	0
7	85	.001	0	0
8	0	.007	.008	.02
9	55	.001	.001	0
10	85	.006	.008	.01
11**	85	.001	0	0
12	0	.067	.056	.12
13	24	0	.003	0
14	55	.031	.016	.04
15*	0	0	0	0
16	55	.001	.005	.01
17	116	.001	0	0
18	55	.008	.051	.06
19	0	.013	.015	.03
20	55	.002	.008	.01

* Glassport Sampler
**Liberty Borough Sampler

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
(Data listed on this page were measured at a wind speed too low for proper modeling.)
Wind Direction: 331°
Wind Velocity: Full Scale - 8 m/sec @ 2926 meters above river level
Model - 0.22 m/sec @ 1.22 meters above river level

Sampling Point No (See Fig 37-39)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant	Clairton & Irvin Excluding Claus	Total Clairton Claus & Irvin
1	55	U	.004	0
2	0	U	.005	.01
3	116	U	0	0
4	55	U	.001	0
5*	0	U	.010	.01
6	85	U	.005	.01
7	24	U	.001	0
8	0	U	.012	.01
9	116	U	.005	.01
10**	85	U	-.002	0
11	34	U	.004	0
12	0	U	.005	.01
13	0	U	.008	.01
14	116	U	-.003	0
15	55	.003	.007	.01
16	0	.017	.007	.02
17	146	.002	.001	0
18	24	.001	.004	.01
19	134	.002	.007	.01
20	158	.002	-.001	0

* Glassport Sampler
**Liberty Borough Sampler

Note: U designates sampling points are upwind of source and, thus will not contribute to the total SO_2 levels.

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 331°
Wind Velocity: Full Scale - 15 m/sec @ 2926 meters above river level,
6 m/sec @ Liberty Borough School
Model - 0.41 m/sec @ 1.22 meters above river level,
0.16 m/sec @ Liberty Borough School

Sampling Point No (See Fig 37-39)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant	Clairton & Irvin Excluding Claus	Total Clairton Claus & Irvin (Fig 37)
1	55	U	0	0
2	0	U	.023	.02
3	116	U	0	0
4	55	U	0	0
5 *	0	U	.003	0
6	85	U	.008	.01
7	24	U	0	0
8	0	U	.005	.01
9	116	U	.006	.01
10 **	85	.002	0	0
11	24	.001	0	0
12	0	.001	.005	.01
13	0	0	.003	0
14	116	0	0	0
15	55	.001	0	0
16	0	.059	.021	.08
17	146	0	.003	0
18	24	0	0	0
19	134	.012	.008	.02
20	158	.001	.001	0

* Glassport Sampler
**Liberty Borough Sampler

Note: U designates sampling points are upwind of the source and, thus will not contribute to the total SO_2 level.

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 331°
Wind Velocity: Full Scale - 22 m/sec @ 2926 meters above river level,
8.8 m/sec @ Liberty Borough School
Model - 0.60 m/sec @ 1.22 meters above river level,
0.24 m/sec @ Liberty Borough School

Sampling Point No (see Fig 37-39)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant	Clairton & Irvin Excluding Claus	Total Clairton Claus & Irvin (Fig 38)
1	55	U	.001	0
2	0	U	.035	.04
3	116	U	0	0
4	55	U	.005	.01
5*	0	U	.068	.07
6	85	U	.016	.02
7	34	U	.005	.01
8	0	U	.027	.03
9	116	U	.006	.01
10**	85	U	.003	0
11	84	U	.004	0
12	0	U	.005	.01
13	0	U	.063	.06
14	116	U	.008	.01
15	55	.002	.002	0
16	0	.041	.136	.18
17	146	.001	.006	.01
18	34	.001	.009	.01
19	134	.013	.052	.07
20	158	.002	.002	0

* Glassport Sampler
**Liberty Borough Sampler

Note: U designates sampling points are upwind of the source and, thus will not contribute to the total SO_2 level.

Full-Scale Ground Level Concentrations of SO_2 Calculated from Model Test Data
Wind Direction: 331° (with inversion)
Wind Velocity: Full Scale - 15 m/sec @ 2926 meters above river level,
9 m/sec @ Liberty Borough School
Model - 0.41 m/sec @ 1.22 meters above river level,
0.25 m/sec @ Liberty Borough School

Sampling Point No (See Fig 37-39)	Ground Elevation Above River (meters)	SO_2 Concentration Levels (ppm)		
		Claus Plant	Clairton & Irvin Excluding Claus	Total Clairton Claus & Irvin (Fig 39)
1	55	U	.028	.03
2	0	U	.005	.01
3	116	U	0	0
4	55	U	.008	.01
5 *	0	U	.004	0
6	85	U	.001	0
7	24	U	.008	.01
8	0	U	.003	0
9	116	U	0	0
10 **	85	U	0	0
11	24	U	.004	0
12	0	U	0	0
13	0	U	.145	.15
14	116	U	.001	0
15	55	.002	.046	.05
16	0	.037	.068	.11
17	146	.001	.001	0
18	24	.003	.045	.05
19	134	.012	.029	.04
20	158	.001	0	0

* Glassport Sampler
** Liberty Borough Sampler

Note: U designates sampling points are upwind of the source and thus, will not contribute to the total SO_2 level.

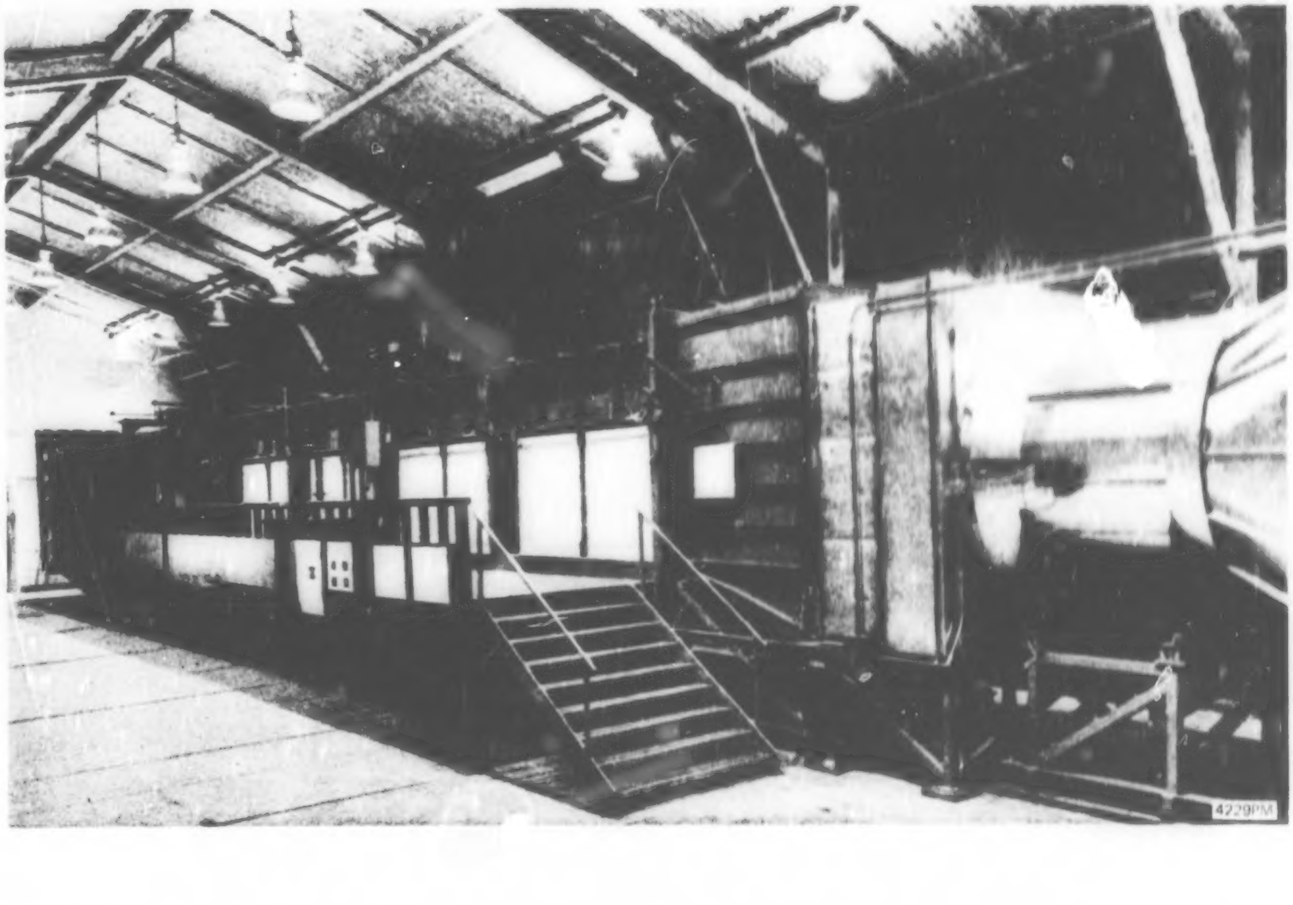

4229PM
119 FT
80 FT
TEST SECTION
NOMINAL SIZE = 6 FT HIGH X 8 FT WIDE
FAN AND NOISE-ATTENUATOR SYSTEM
FLOW DEVELOPMENT REGION
50 FT
TEST SECTION
30 FT

Figure 1 THE CALSPAN ATMOSPHERIC SIMULATION FACILITY (ASF)

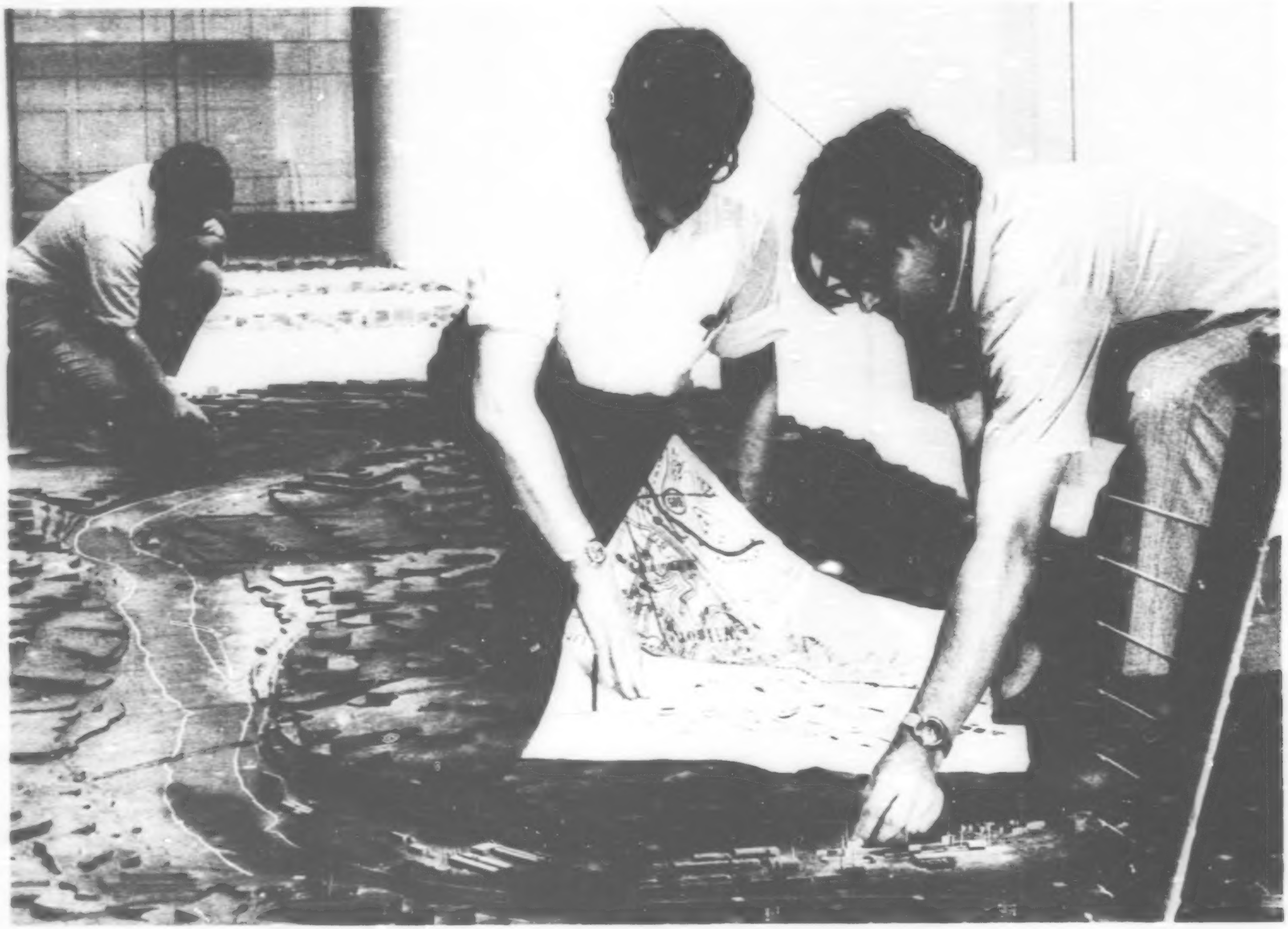


Figure 2 MODEL INSTALLED IN THE ASF FOR S-W WIND STUDY

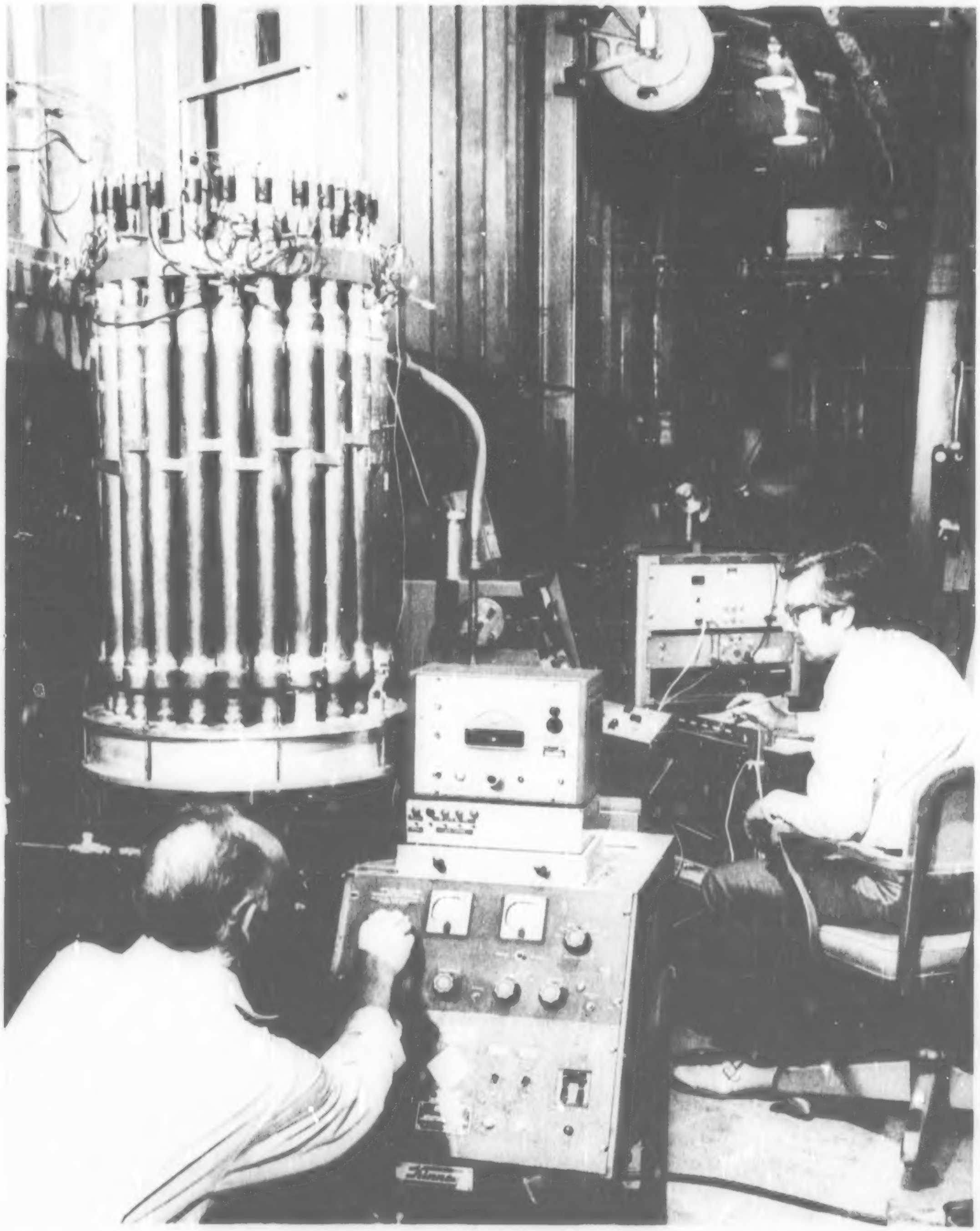
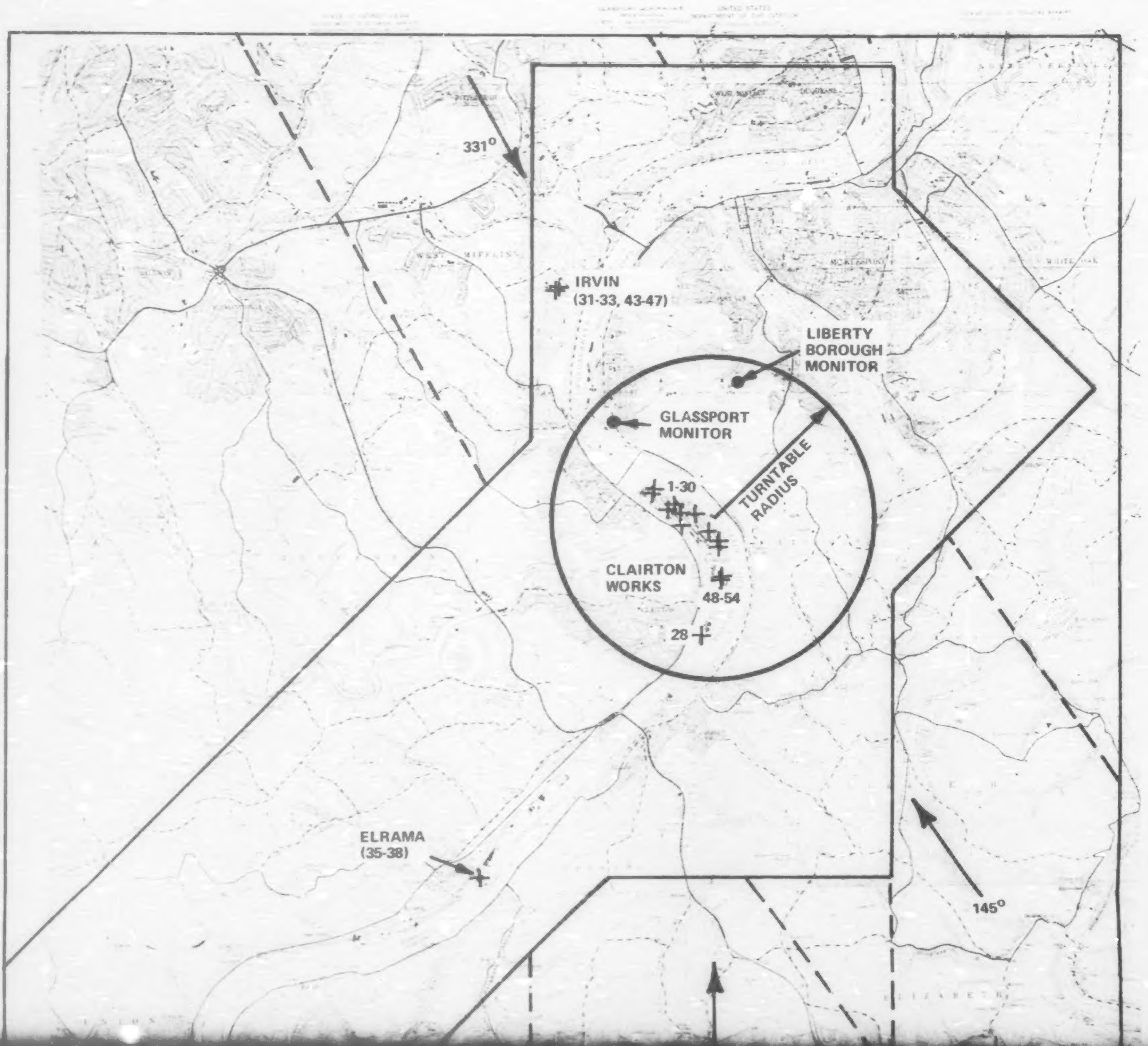
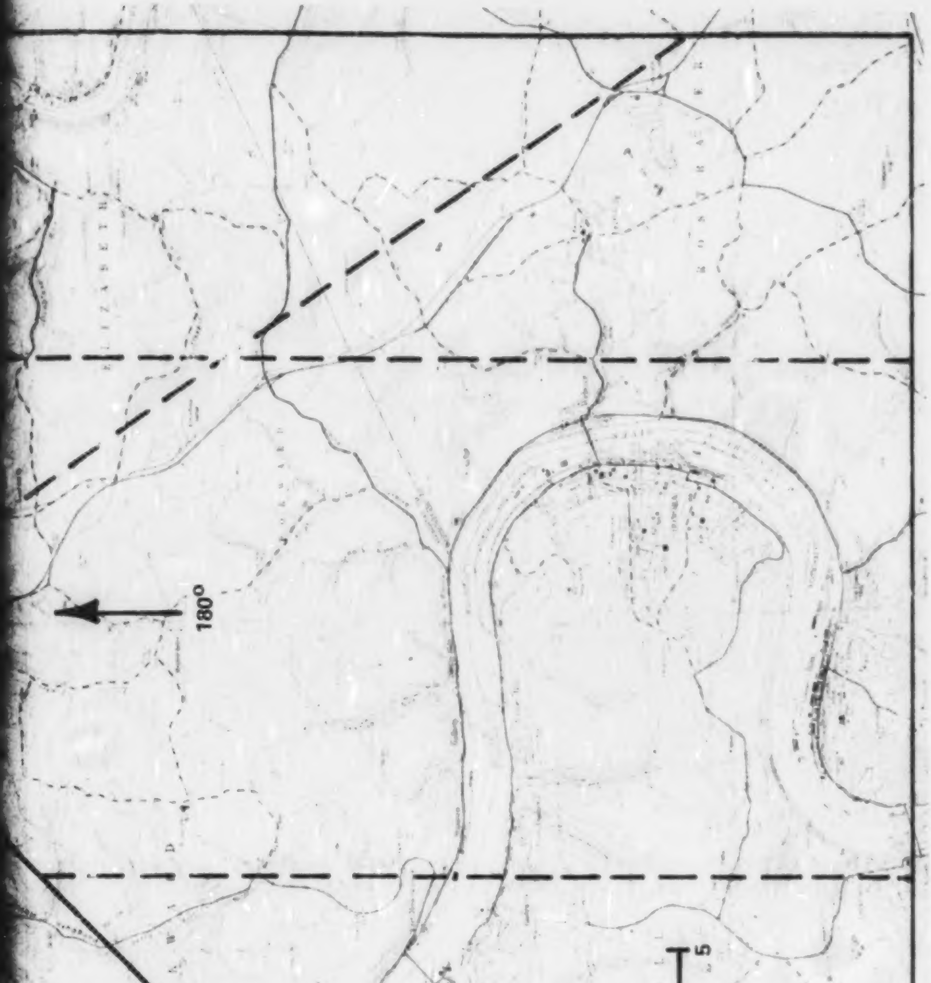


Figure 3 CONCENTRATION SAMPLING SYSTEM


331°
IRVIN
(31-33, 43-47)
LIBERTY
BOROUGH
MONITOR
GLASSPORT
MONITOR
1-30
TURNTABLE
RADIUS
CLAIRTON
WORKS
48-54
28
ELRAMA
(35-38)
145°


180°
MITCHELL
(39-42)
225°
0
1
2
3
4
5
FULL SCALE KILOMETERS
(MODEL SCALE 1:2400)

NOTES:

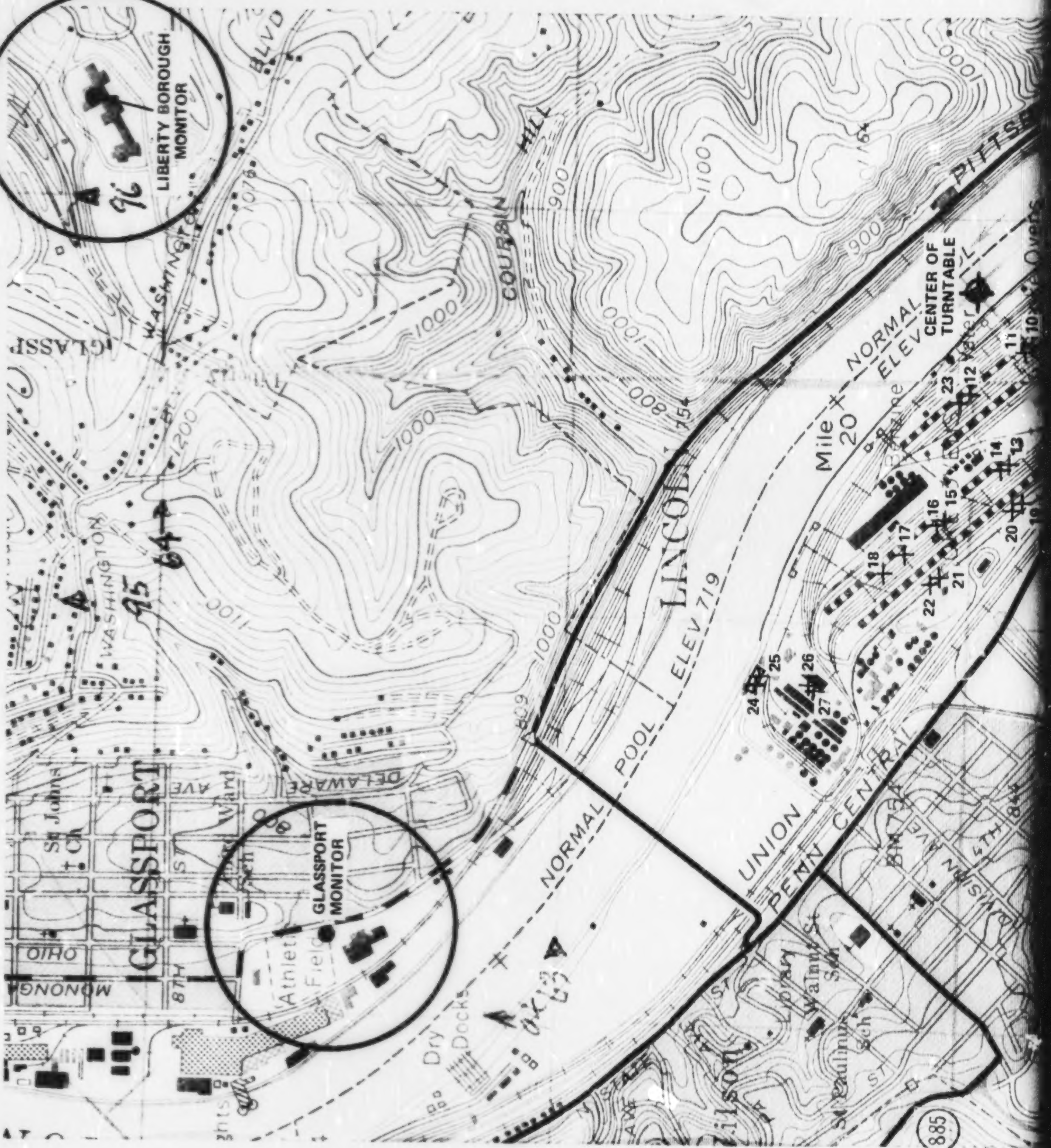
1) TERRAIN MODEL IS SHOWN ENCLOSED BY SOLID LINES

2) DASHED LINES FOR EACH WIND DIRECTION INDICATE UPSTREAM AREAS MODELED WITH RANDOM ROUGHNESS ELEMENTS

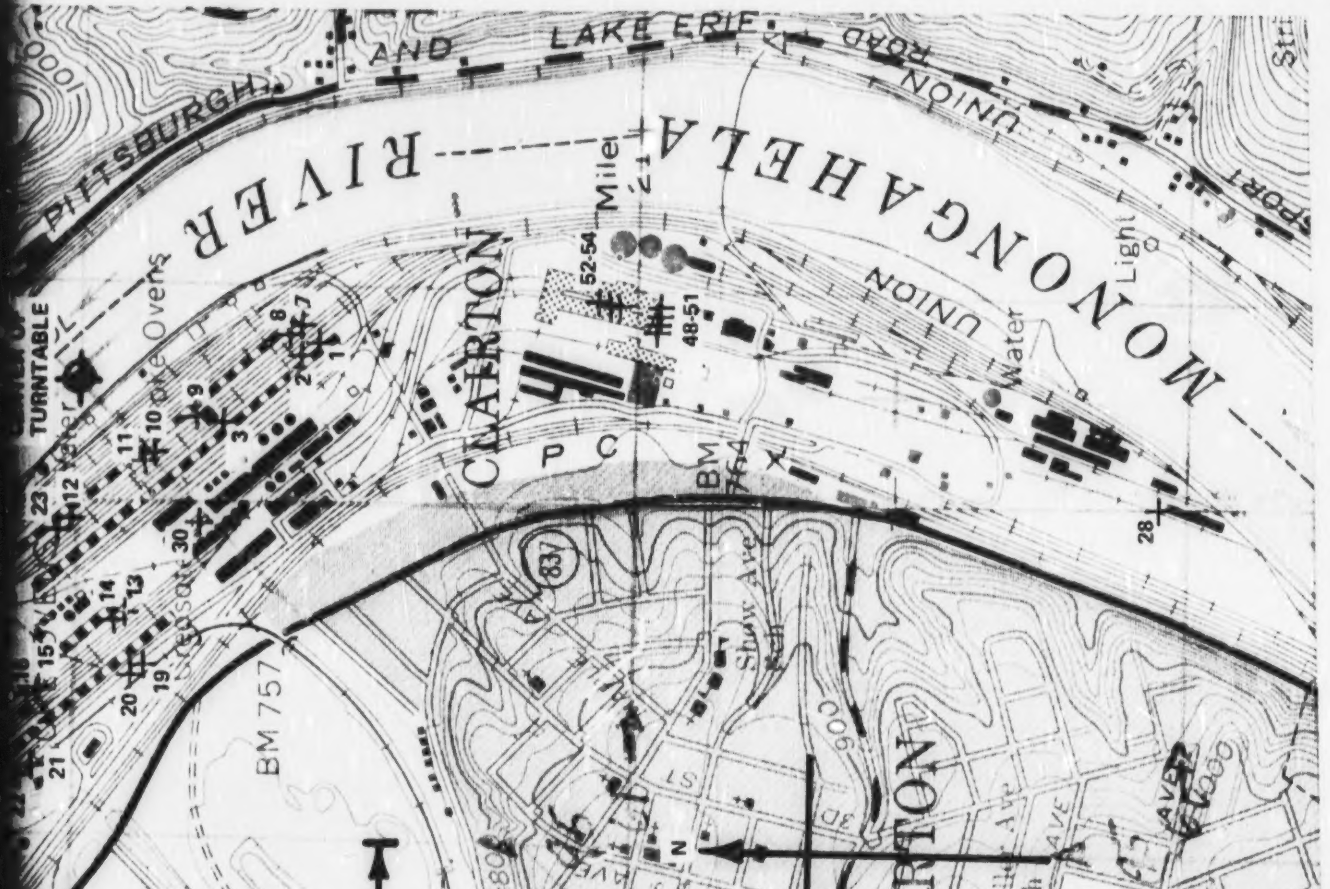
3) NUMBERS ADJACENT TO SOURCE LOCATIONS CORRESPOND TO SOURCE INVENTORY LISTED IN TABLE III

Figure 4 SOURCE LOCATIONS AND TERRAIN AREAS MODELED IN THE ATMOSPHERIC SIMULATION FACILITY

B


LIBERTY BOROUGH MONITOR
96
GLASSPORT MONITOR
CENTER OF TURNTABLE
GLASSPORT
WASHINGTON
BLVD
COURSIN HILL
LINCOLN
ELEV 719
NORMAL POOL
NORMAL POOL ELEV
Mile 20
UNION
PENN CENTRAL
PITTSB
95
64
65
DELAWARE AVE
OHIO
MONONGA
8TH
St Johns Ch
Athletic Field
Dry Docks
Ovens
1000
1100
1200
900
800
885

A



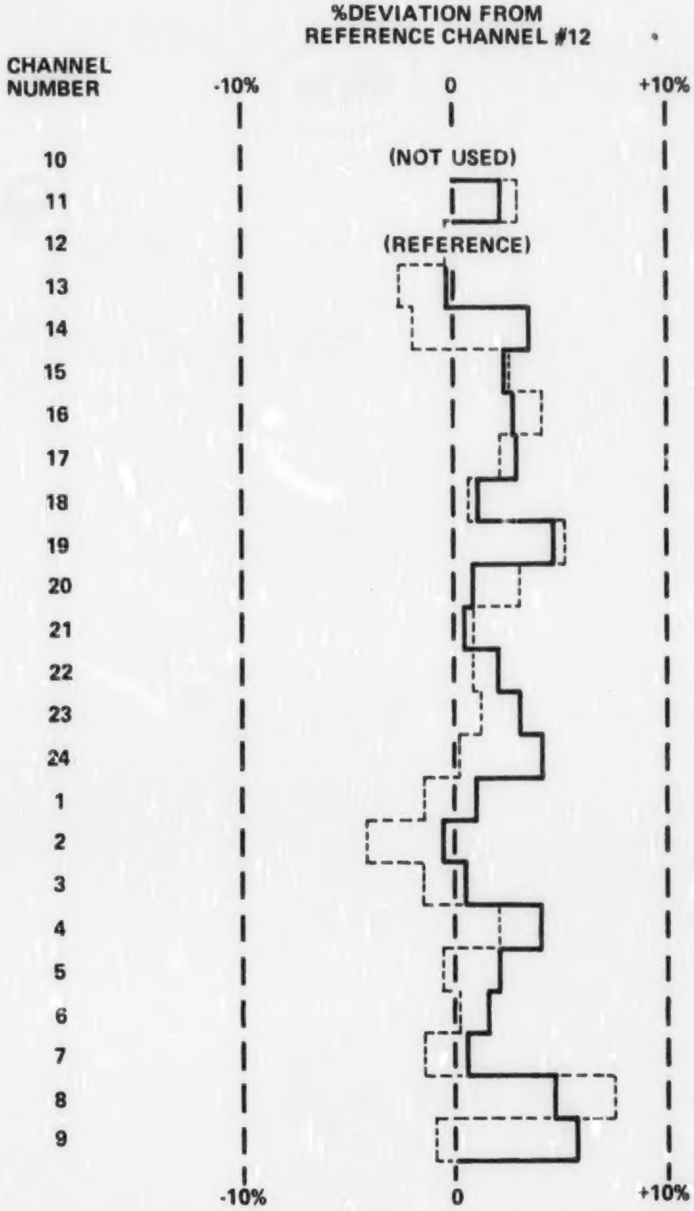
1 KILOMETER FULL SCALE (MODEL SCALE 1:2400)

NUMBERS ADJACENT TO SOURCE LOCATIONS CORRESPOND TO SOURCE INVENTORY LISTED IN TABLE III

MONONGAHELA RIVER
PITTSBURGH AND LAKE ERIE ROAD
UNION
CLAIRTON
TURNTABLE
Coke Ovens
N
52-54
48-51
28
23
30
1
2
3
7
8
9
10
11
12
13
14
15
19
20
21
Mile 21
BM 757
837
Shaw Ave
St Clares Sch
High Sch
Miller Sch
ST CLAIR AVE
BAKER
THOMPSON
FARNSWORTH AVE
PINE LANE
LARGE ST
WESTERN
Slag Dump
Creek
CITY PARK
Swimming Pool
4TH AVE
844
900
800
Water
Light

Figure 5 LOCATION OF SOURCES MODELED IN CLAIRTON COKE WORKS

B



SOLID LINE: INITIAL CALIBRATION 6/9/75 WITH 925 ppm He in AIR
DASHED LINE: FINAL CALIBRATION 8/6/75 WITH 50 ppm He in AIR

Figure 6 CALIBRATION OF SAMPLING CHANNELS

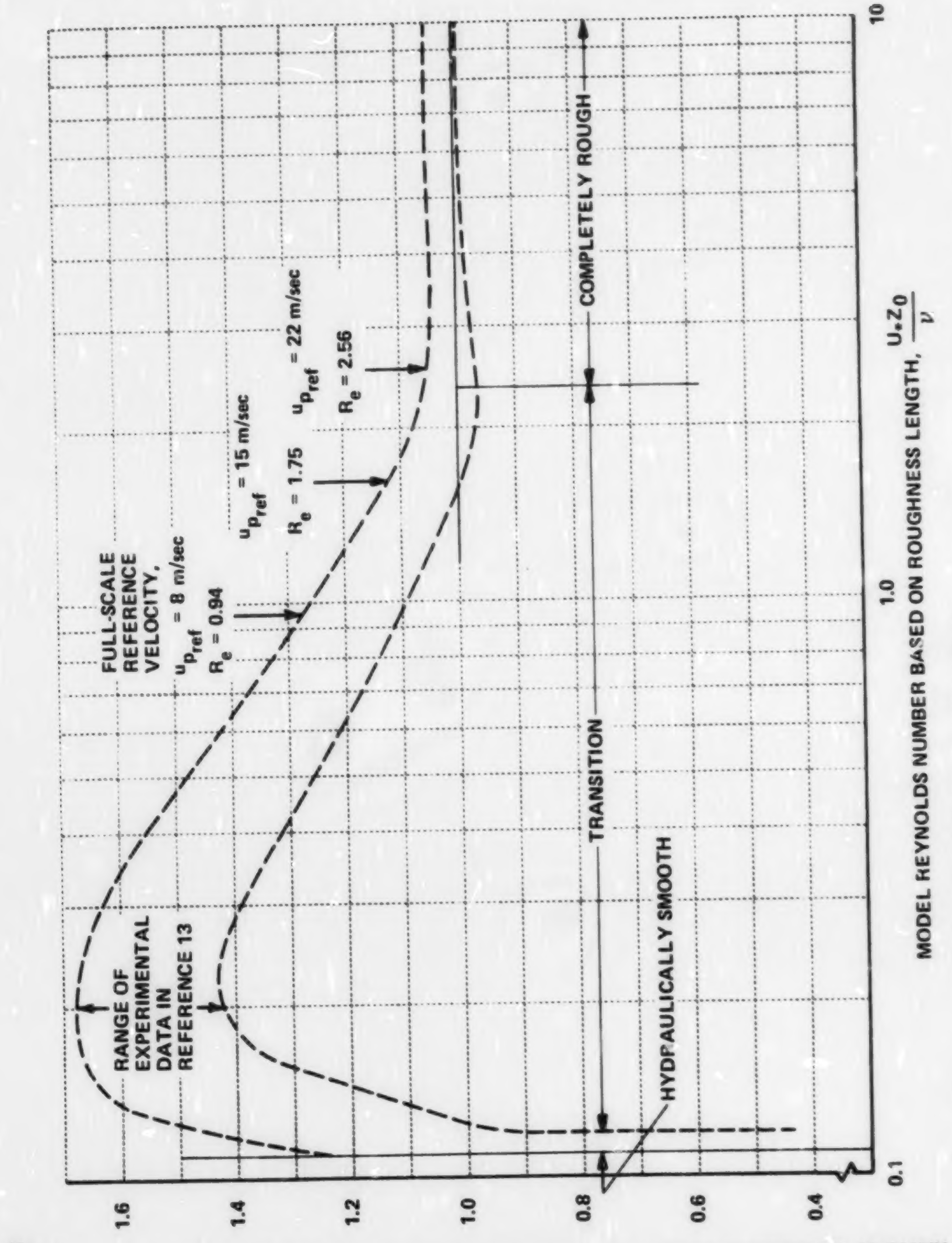


Figure 7 EFFECT OF GROUND-ROUGHNESS REYNOLDS NUMBER ON CHARACTERISTIC GROUND-ROUGHNESS LENGTH

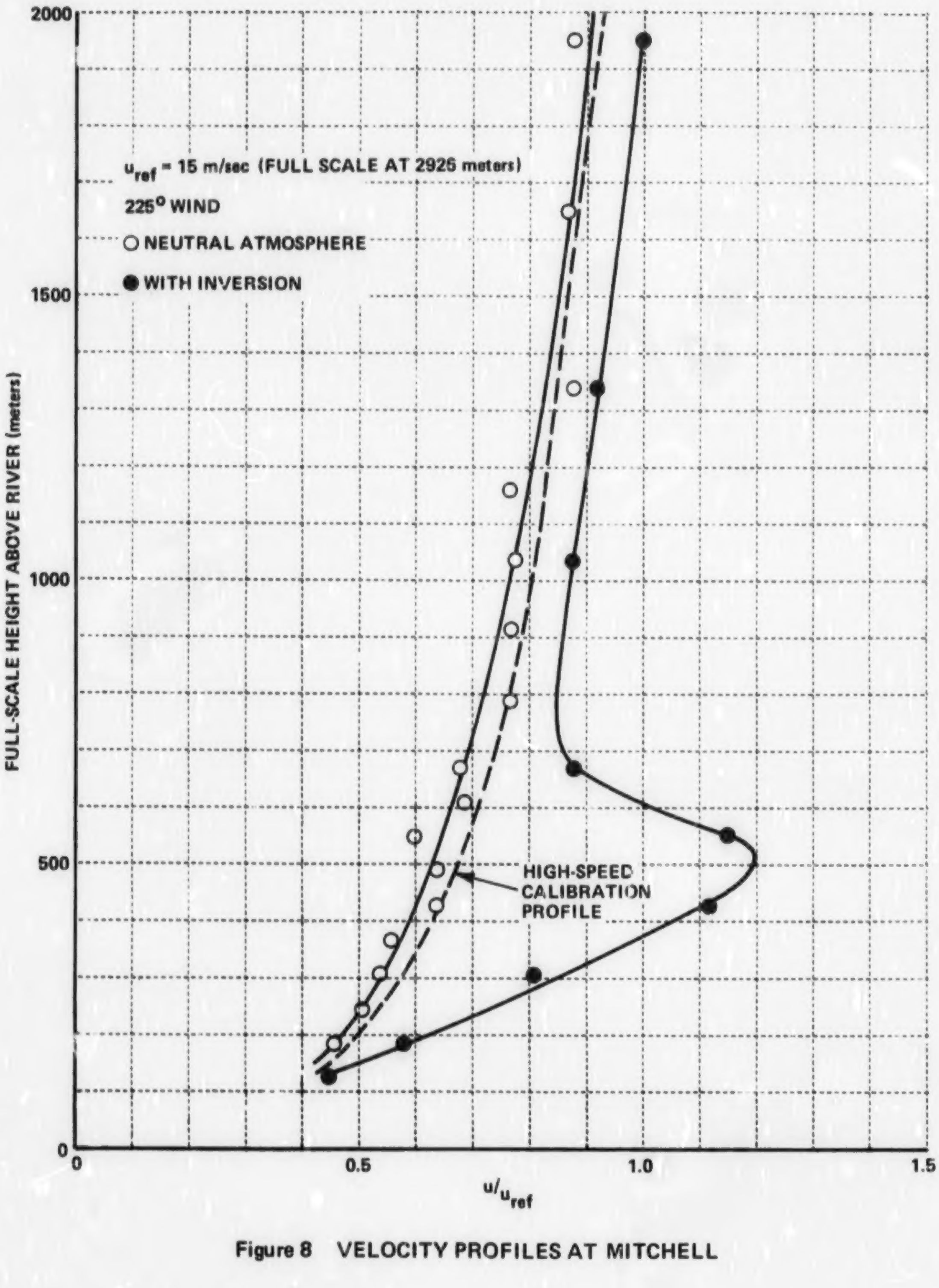


Figure 8 VELOCITY PROFILES AT MITCHELL

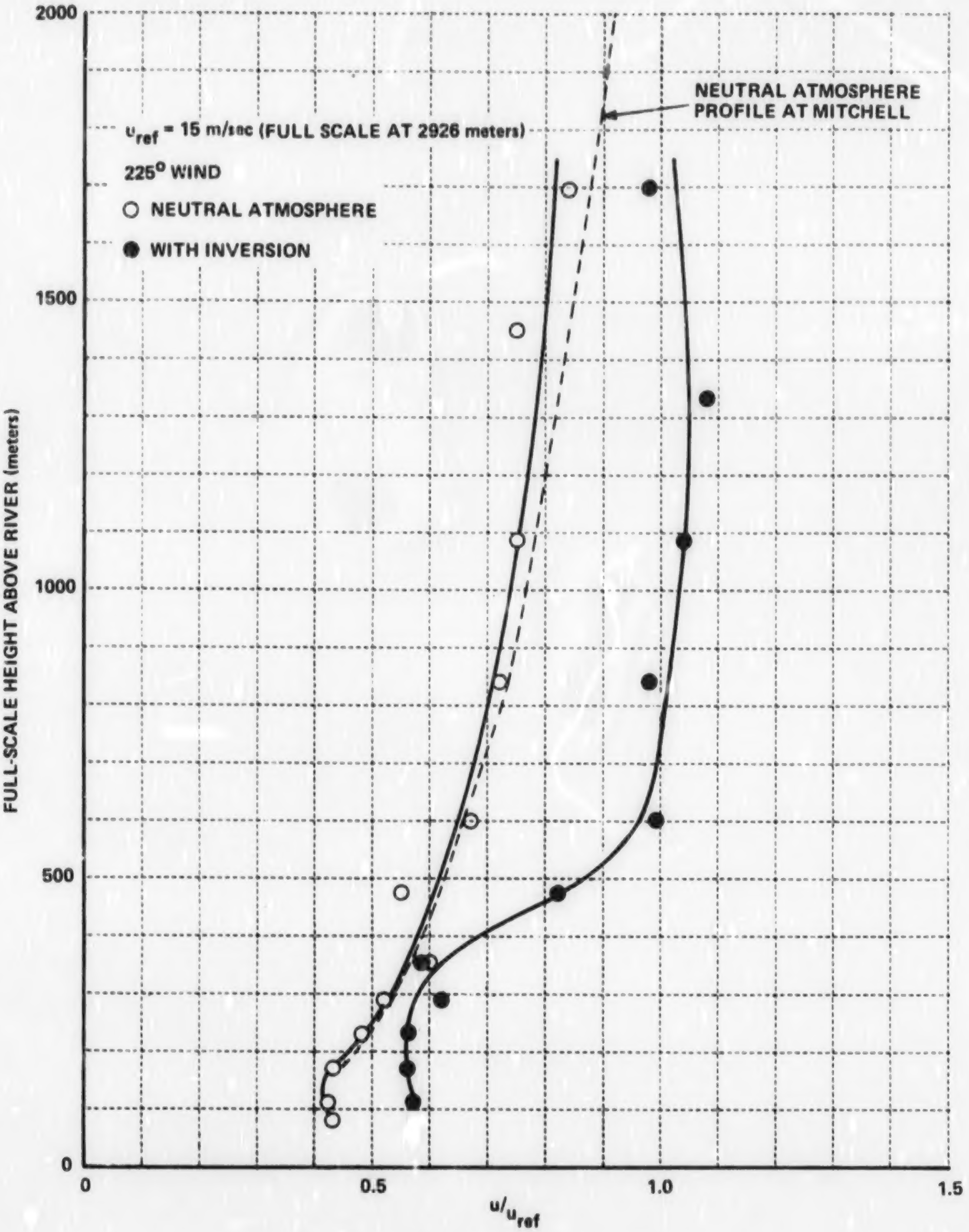


Figure 9 VELOCITY PROFILES AT ELRAMA

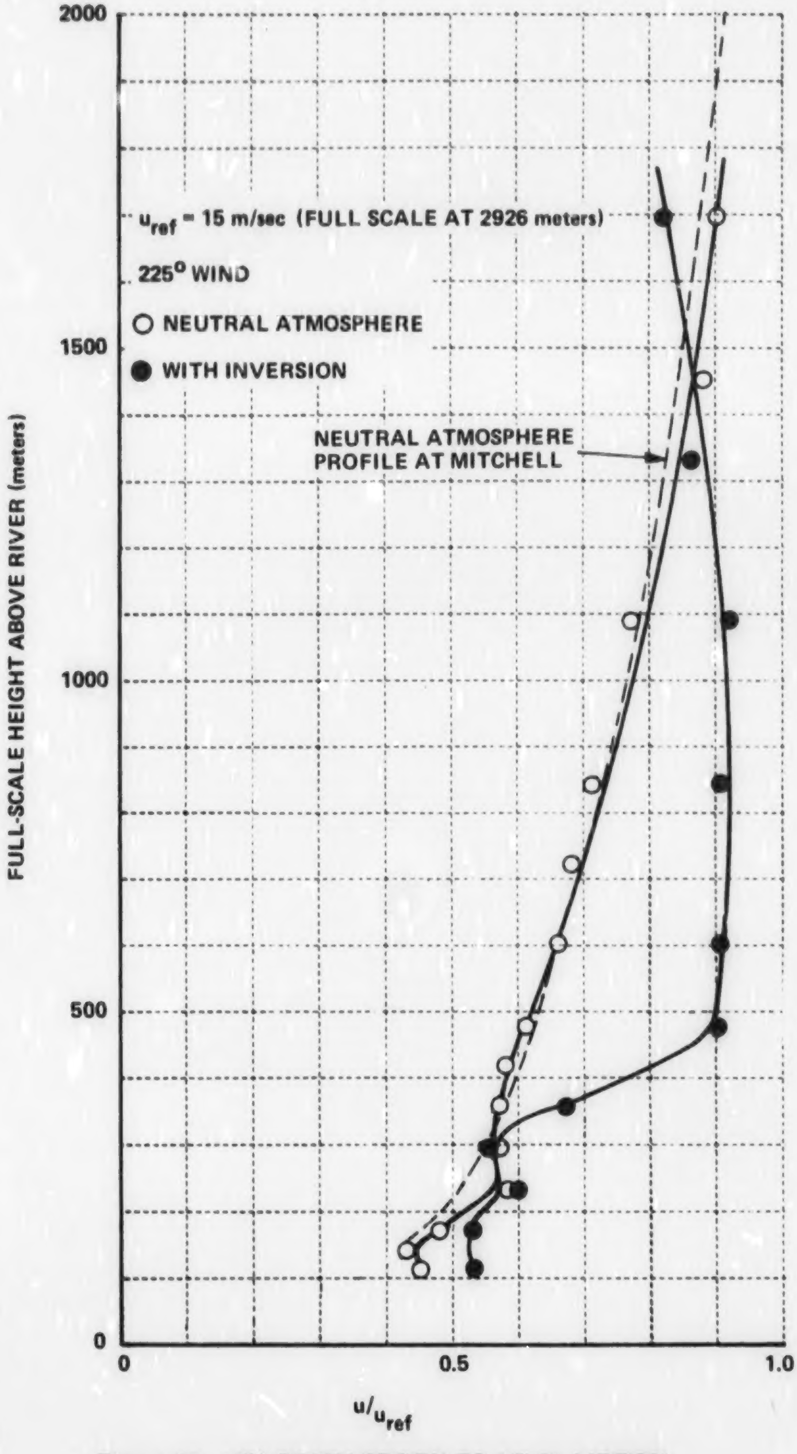


Figure 10 VELOCITY PROFILES AT CLAIRTON

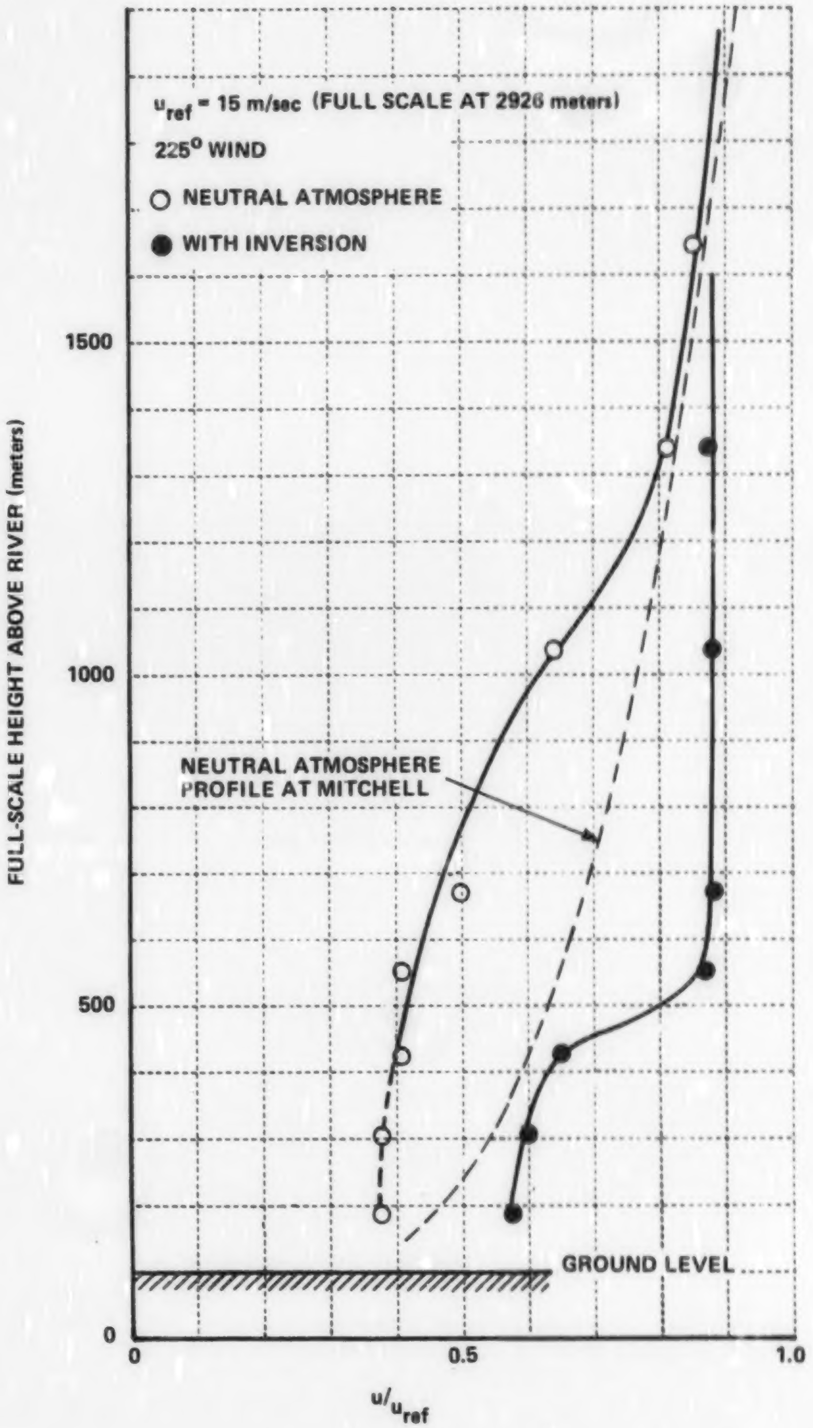


Figure 11 VELOCITY PROFILES AT LIBERTY BOROUGH SCHOOL

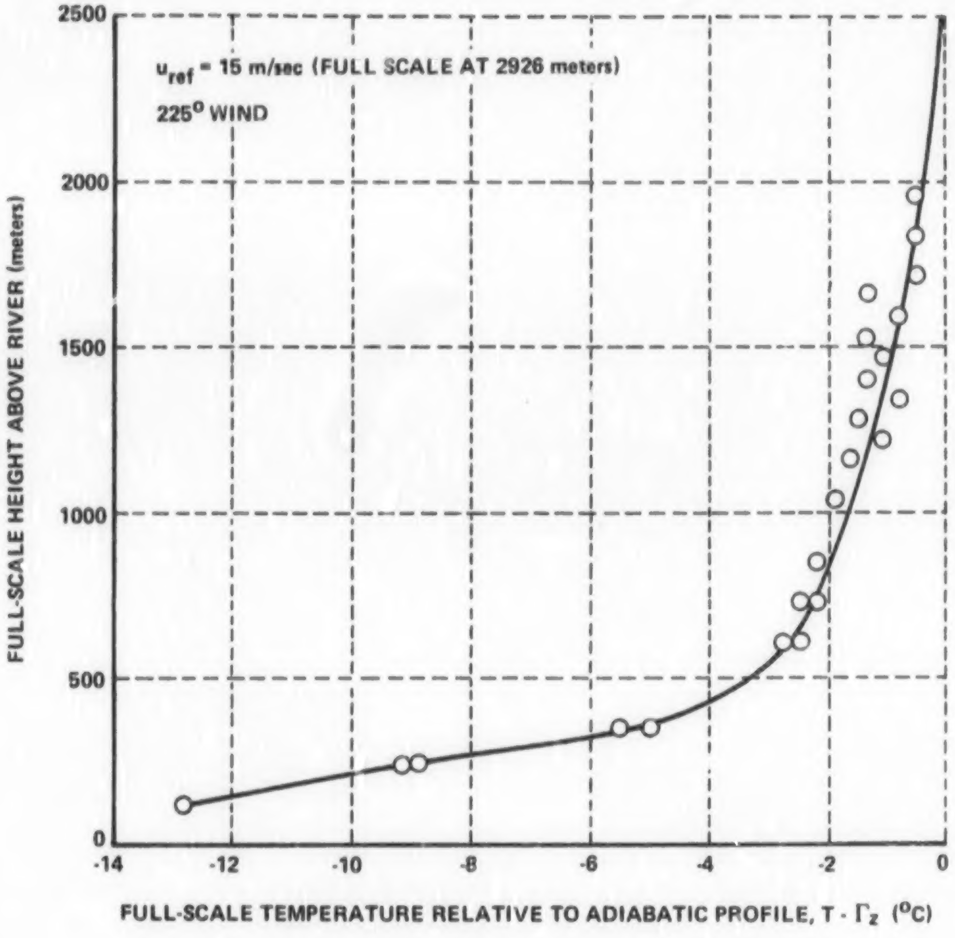


Figure 12 INVERSION TEMPERATURE PROFILE AT MITCHELL

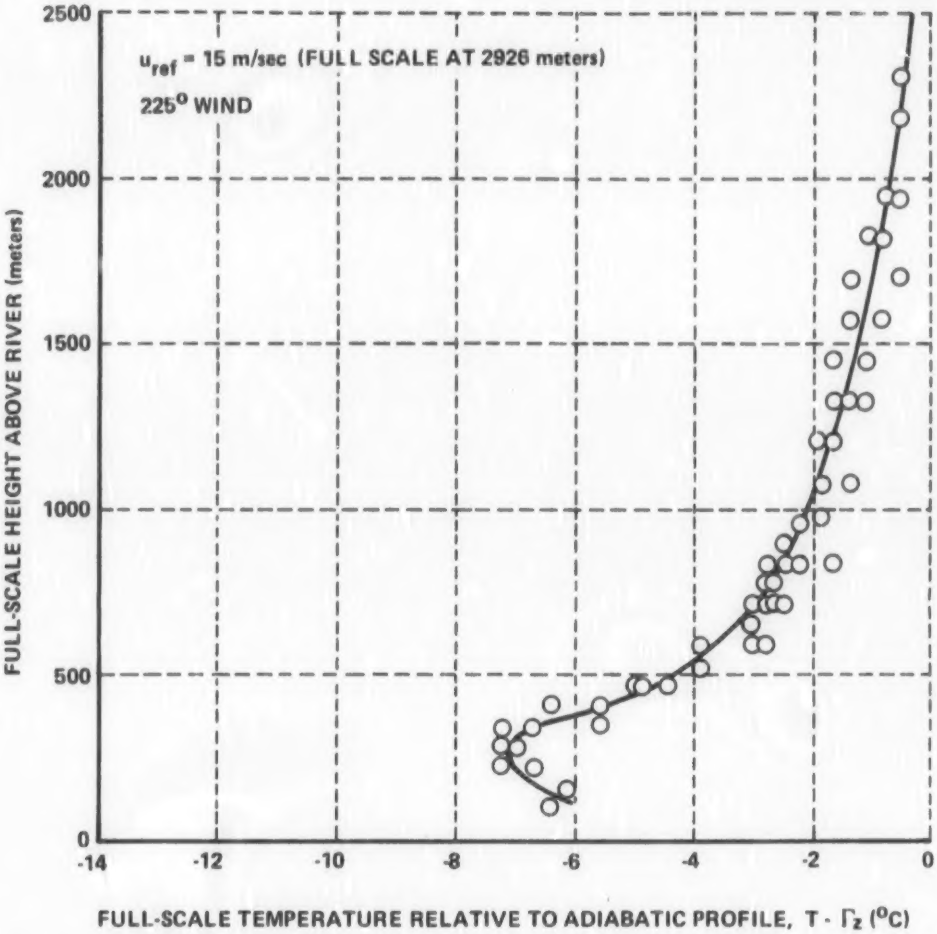


Figure 13 INVERSION TEMPERATURE PROFILE AT ELRAMA

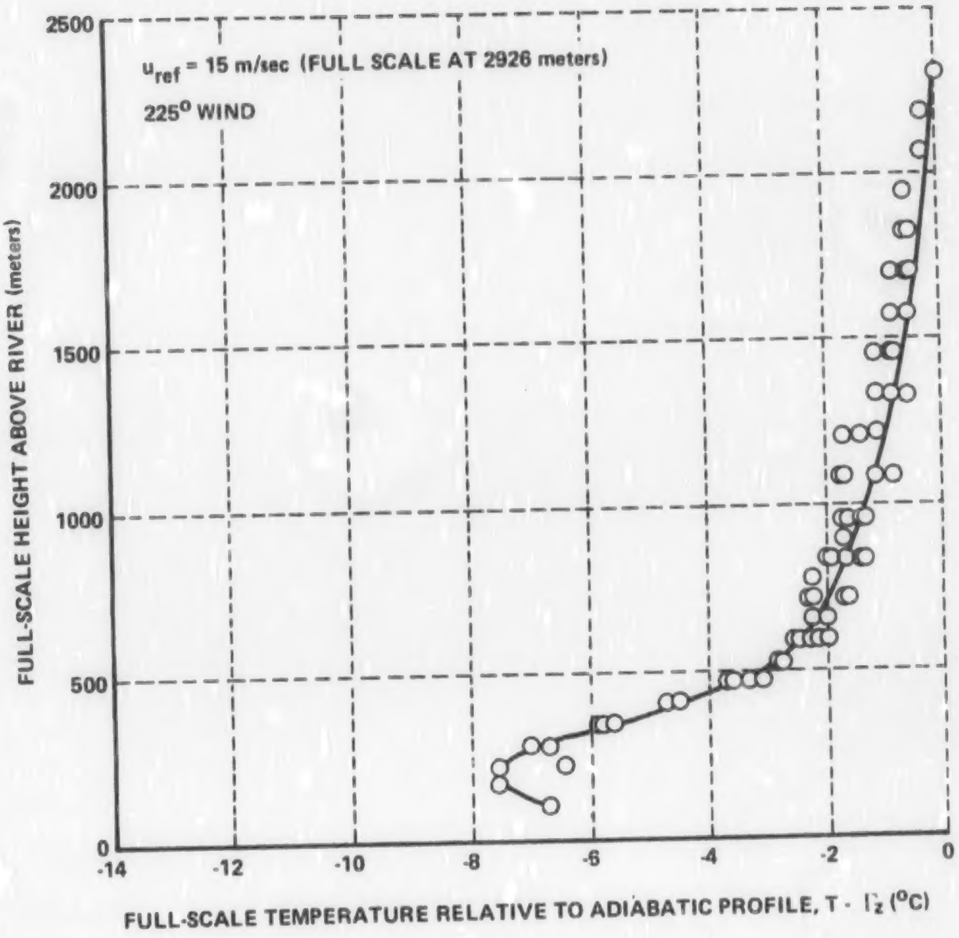


Figure 14 INVERSION TEMPERATURE PROFILE AT CLAIRTON

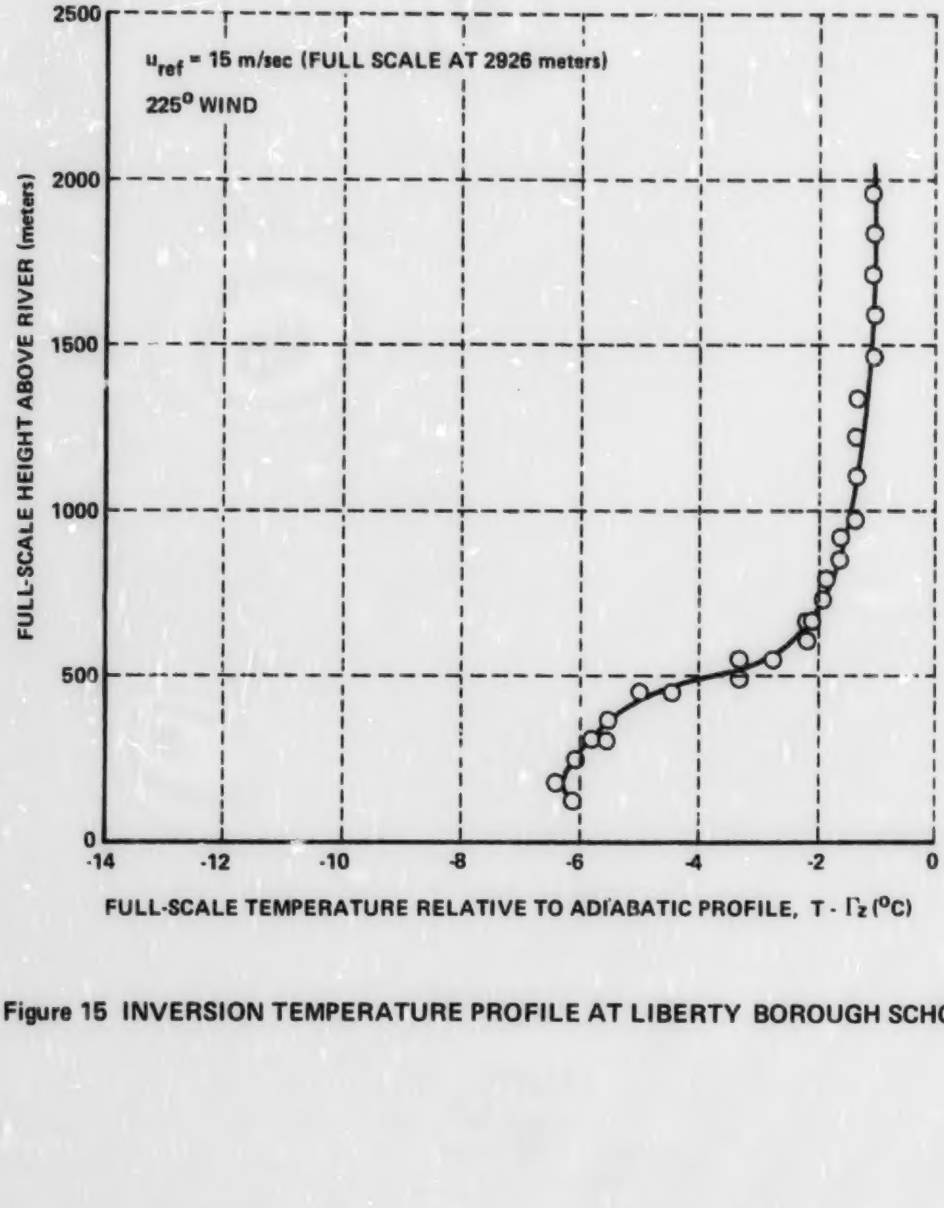
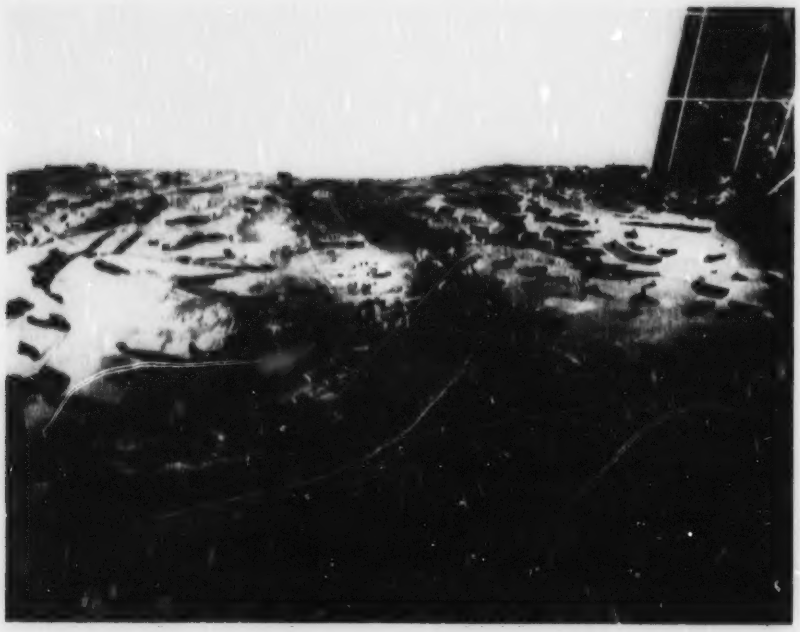
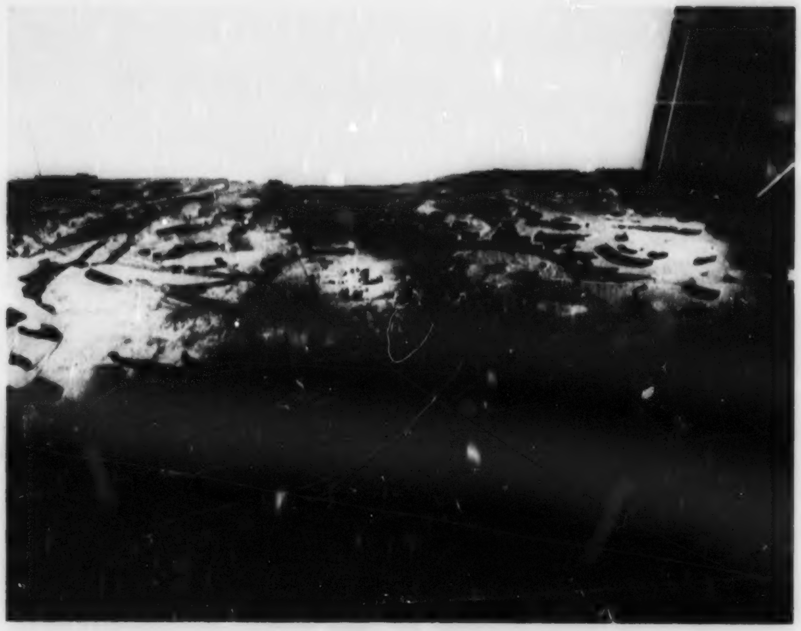


Figure 15 INVERSION TEMPERATURE PROFILE AT LIBERTY BOROUGH SCHOOL



(a) NEUTRAL ATMOSPHERE



(b) WITH INVERSION

Figure 16 SMOKE VISUALIZATION : CLAIRTON AREA : WIND SW AT 15 m/sec AT REFERENCE HEIGHT.

(a) MITCHELL WITH NEUTRAL ATMOSPHERE

(b) ELRAMA WITH INVERSION

Figure 17 SMOKE VISUALIZATION: WIND SW AT 15 m/sec AT REFERENCE HEIGHT

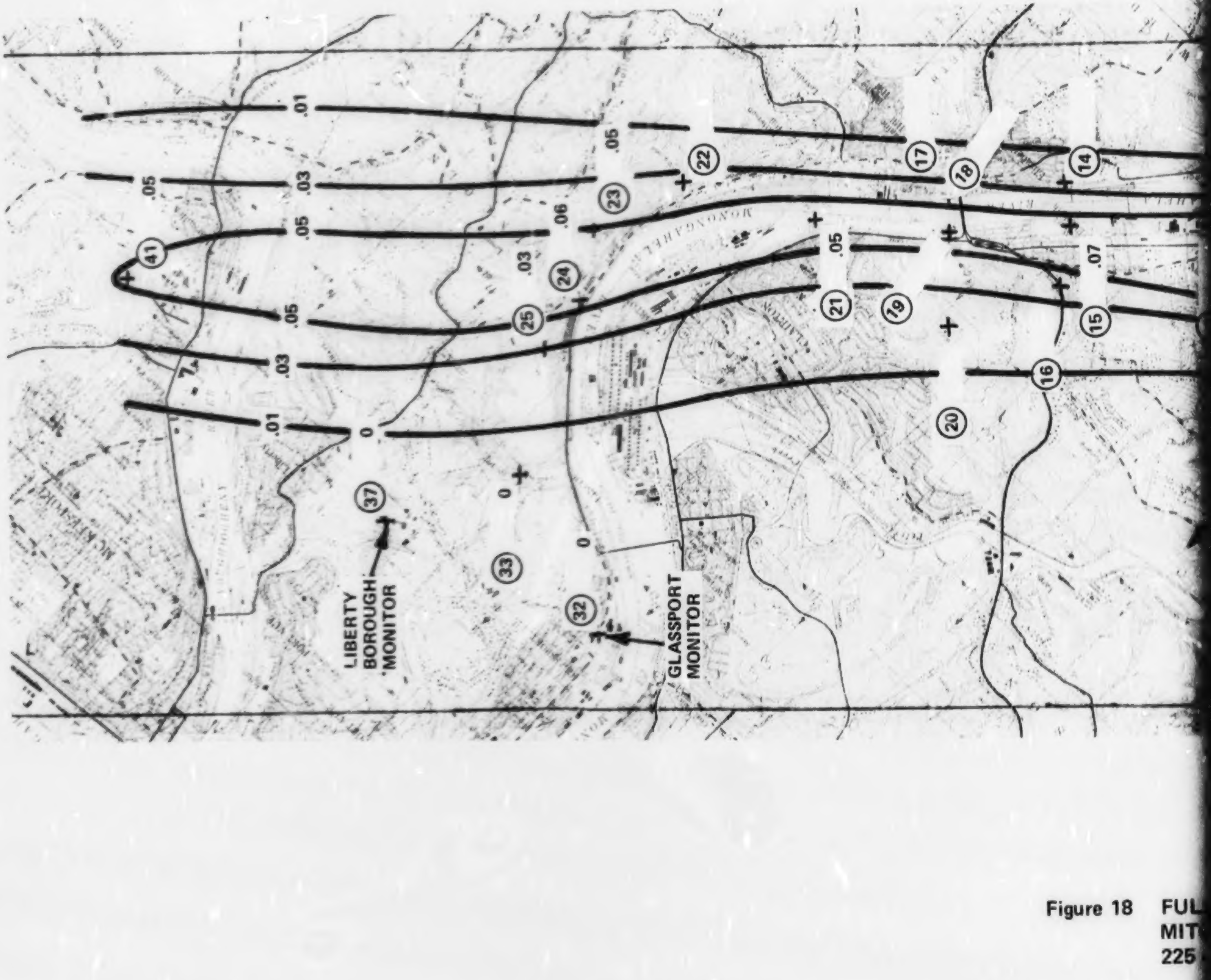
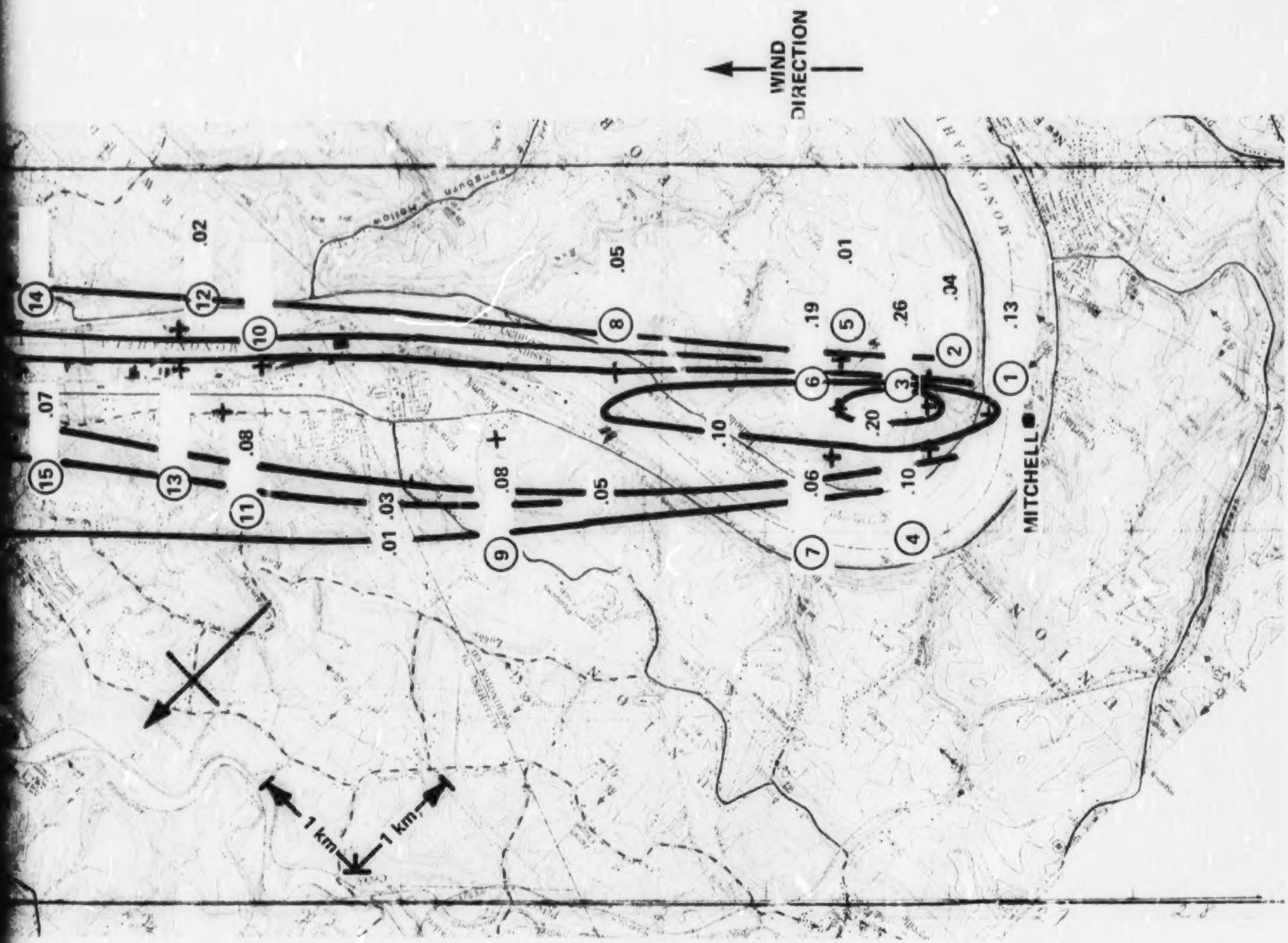

.01
.05
.03
.06
.07
0
⑭
⑮
⑯
⑰
⑱
⑲
⑳
㉑
㉒
㉓
㉔
㉕
㉜
㉝
㊲
㊶
MONONGAHELA
LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR

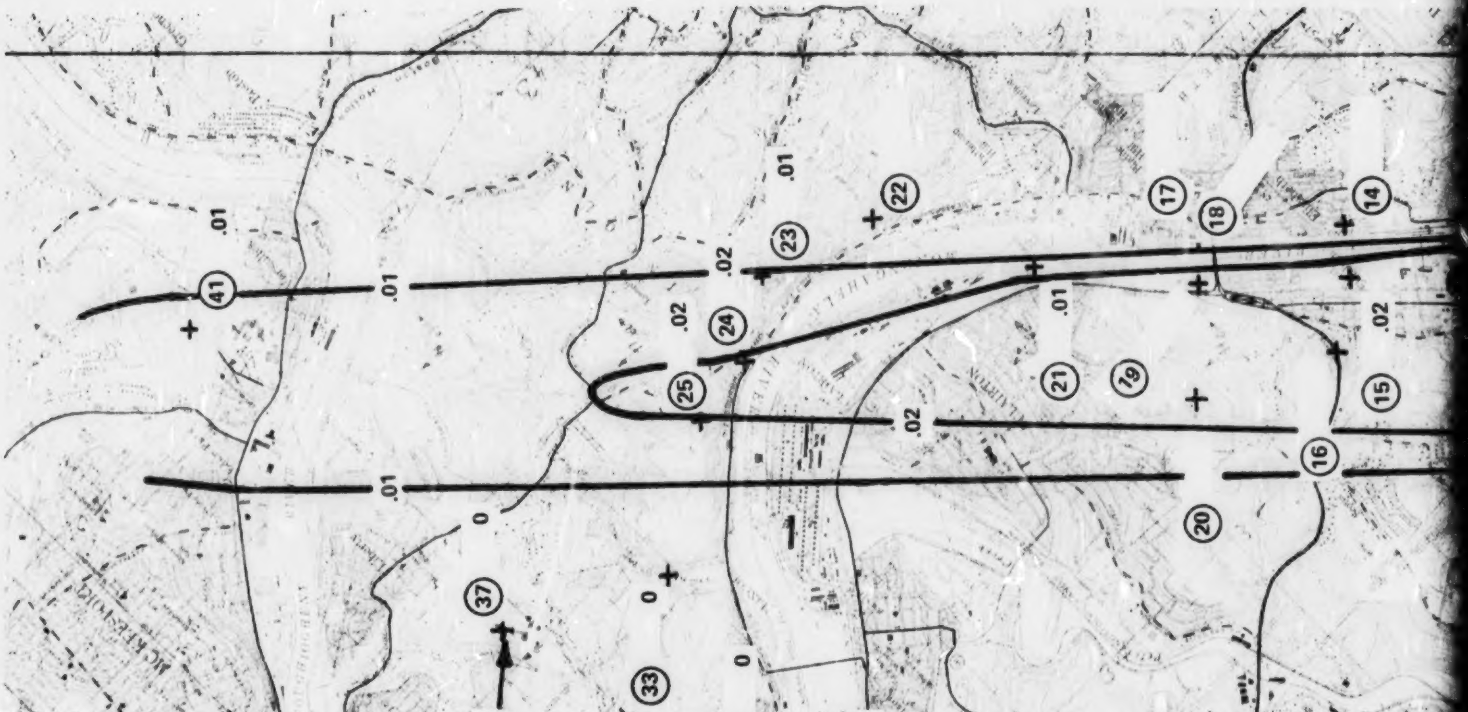
Figure 18 FUL
MIT
225

A


WIND DIRECTION
MITCHELL
1 km
1 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
.02
.05
.01
.34
.26
.19
.13
.07
.08
.10
.20
.06
.10
.05
.08
.03
.01

ure 18 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
MITCHELL SIMULATED, NEUTRAL ATMOSPHERE
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 6 m/sec AT LIBERTY BOROUGH MONITOR

B



LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
.01
.02
0
⑭
⑮
⑯
⑰
⑱
⑲
⑳
㉑
㉒
㉓
㉔
㉕
㉜
㉝
㊲
(41)

Figure 19

A

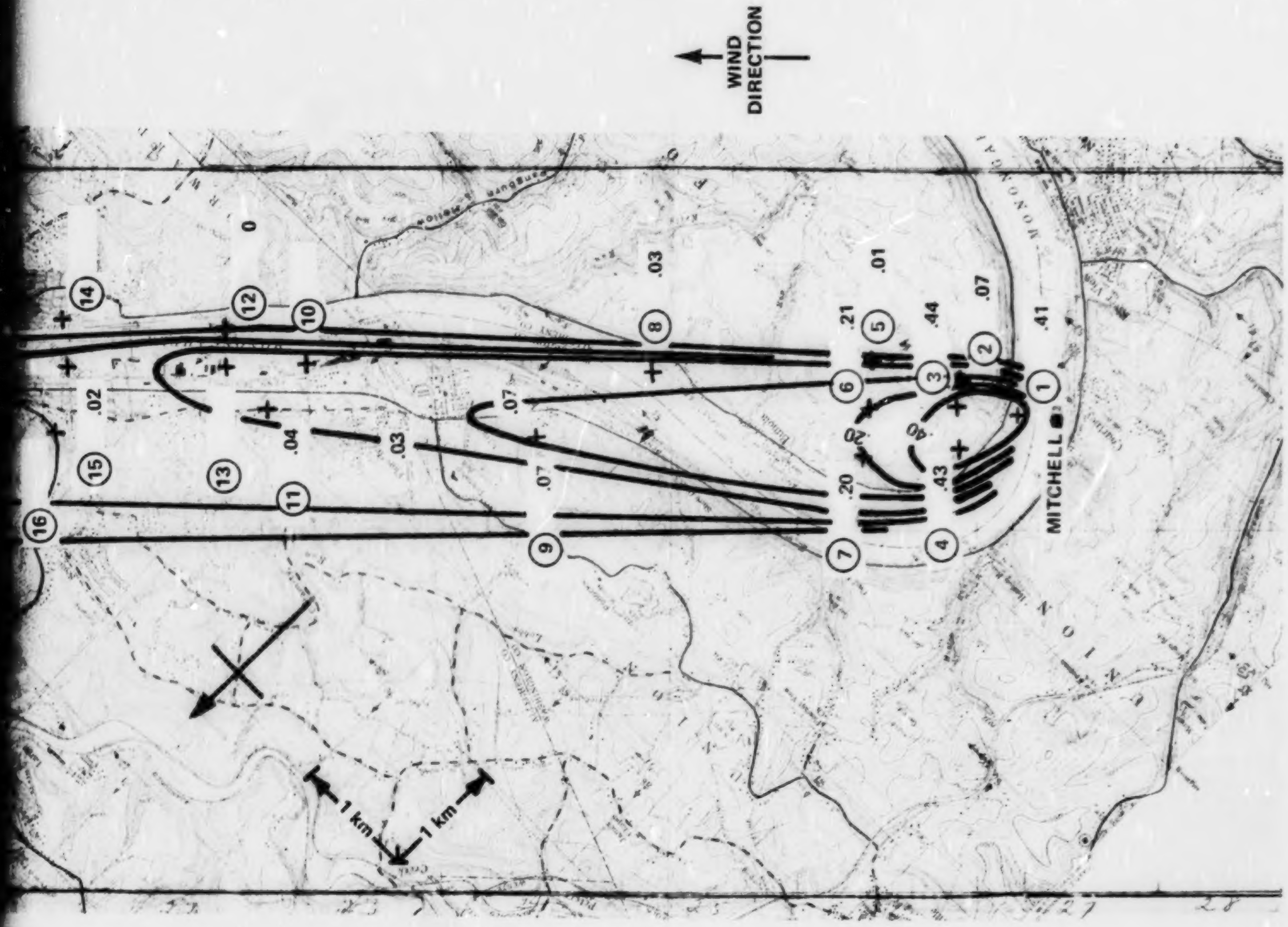

WIND DIRECTION
MITCHELL
1 km
1 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
.41
.07
.44
.01
.21
.03
0
.43
.40
.20
.20
.07
.07
.03
.04
.02

Figure 19 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
MITCHELL SIMULATED, NEUTRAL ATMOSPHERE
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 22 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 8.8 m/sec AT LIBERTY BOROUGH MONITOR

B

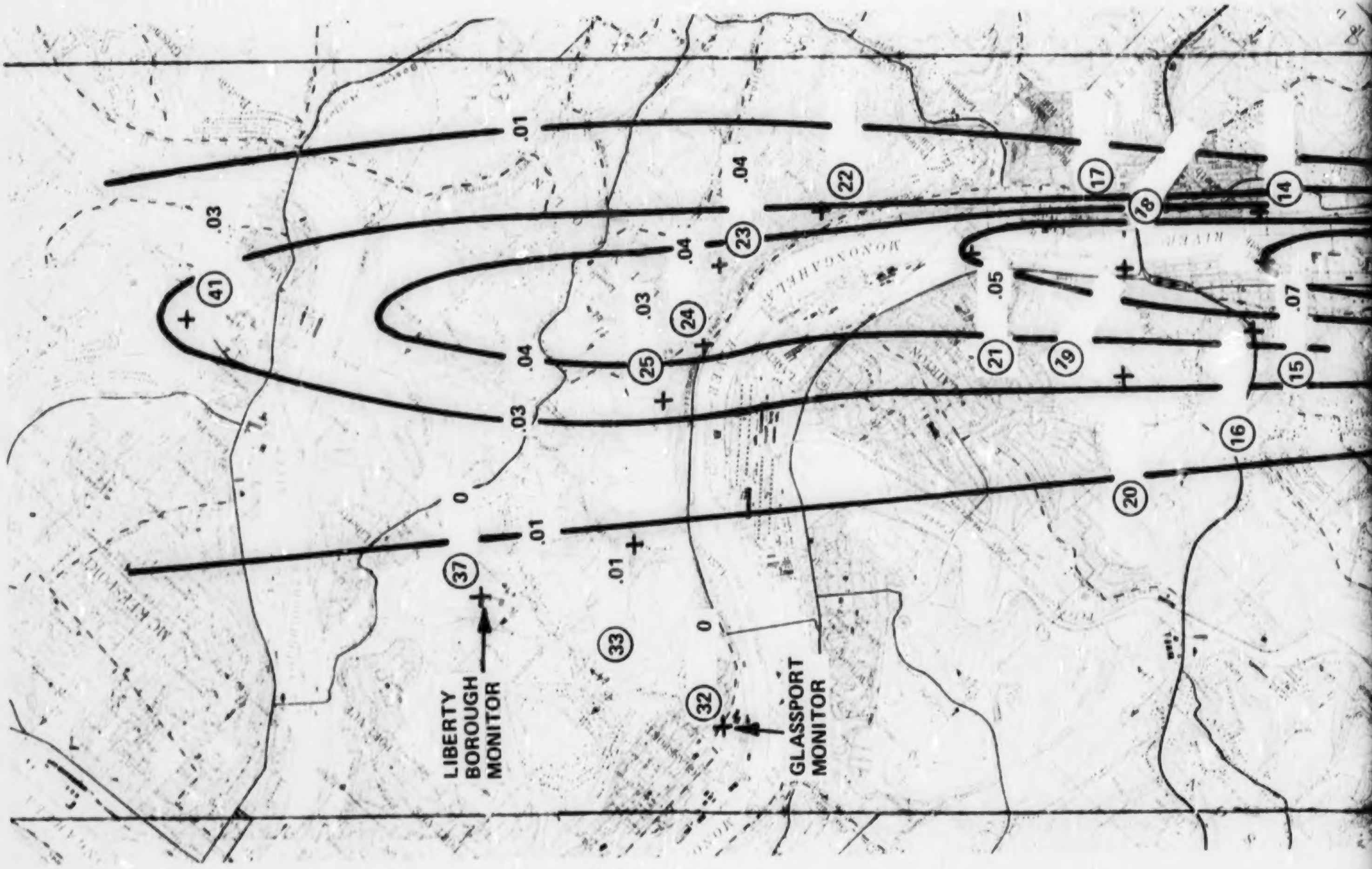
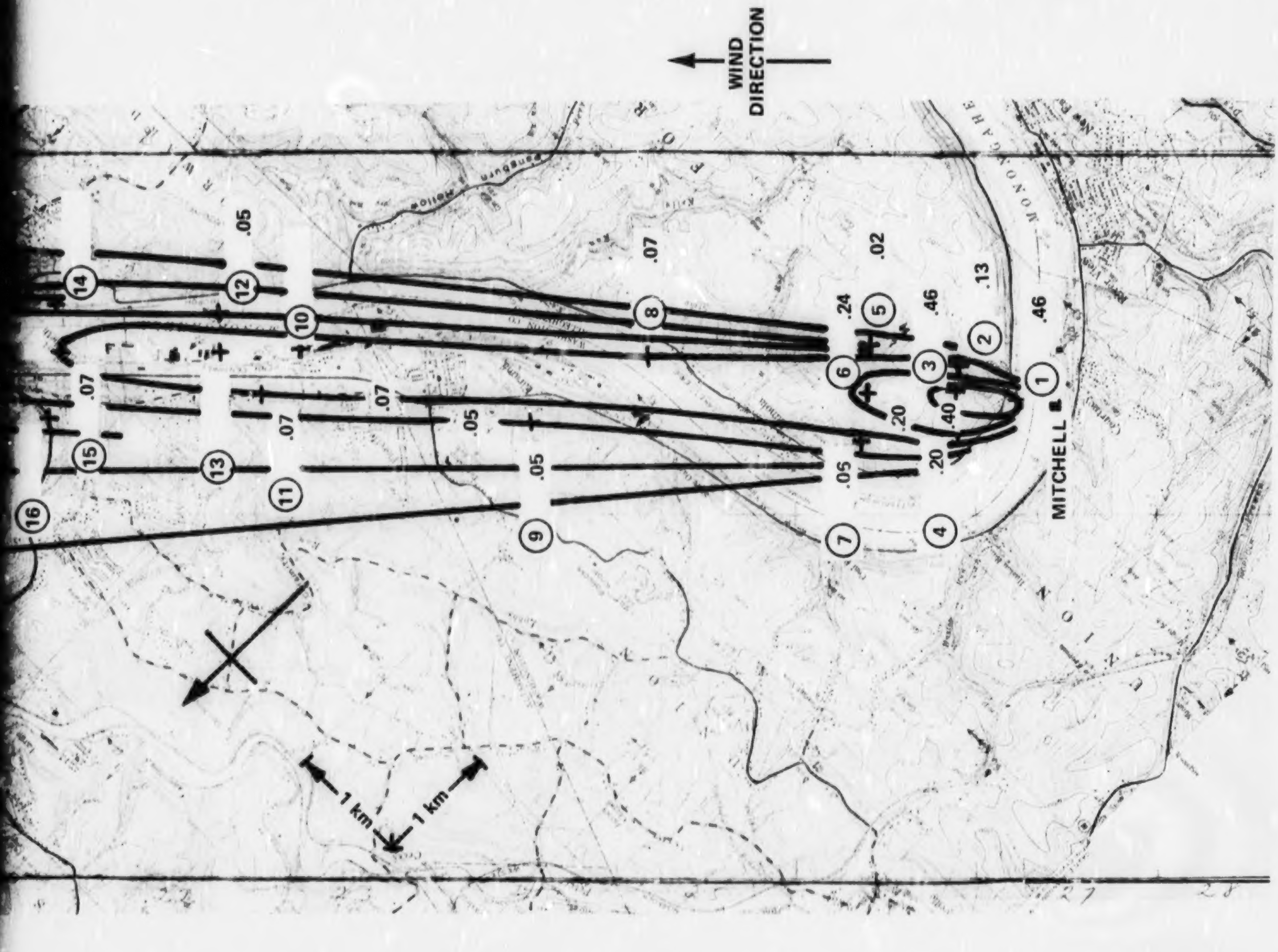

.01
.03
.04
.05
.07
0
41
22
23
24
25
17
18
14
21
19
15
16
20
37
33
32
MONONGAHELA
RIVER
McKEESPORT
LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR

Figure 20 FULL-
MITCH
225 d

A


WIND DIRECTION
MITCHELL
1 km
1 km
MONONGAHELA
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
.46
.46
.13
.02
.24
.07
.05
.20
.40
.20
.05
.05
.07
.05
.07
.07

ure 20 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
MITCHELL SIMULATED, WITH INVERSION
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 9 m/sec AT LIBERTY BOROUGH MONITOR

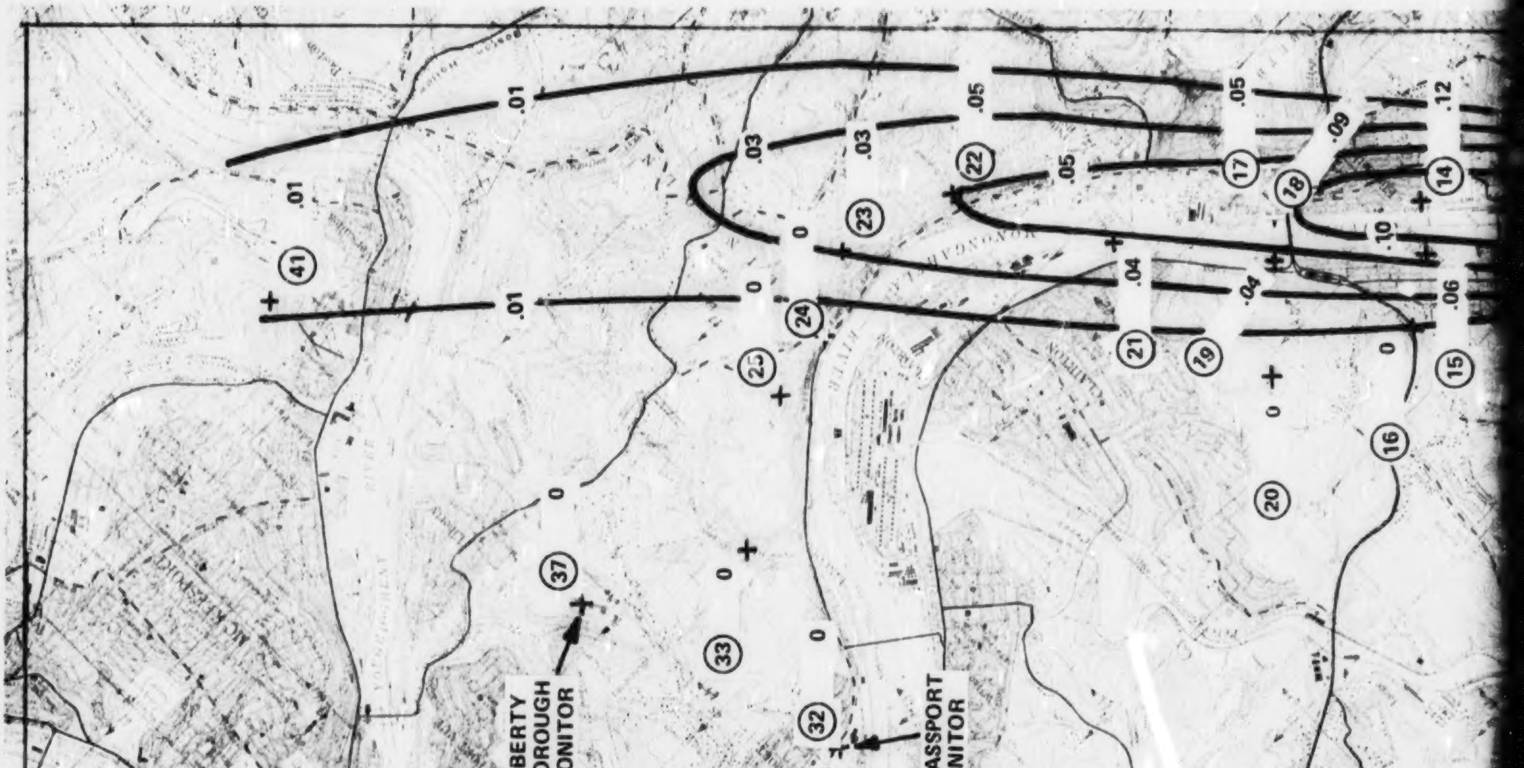

.01
.01
.01
.03
.03
.05
.05
.05
.09
.12
.10
.06
.04
.04
0
0
0
0
0
0
41
23
22
17
18
14
24
21
19
15
25
16
20
37
33
32
LIBERTY
BOROUGH
MONITOR
GLASSPORT
MONITOR

Figure 21 FULL-
ELRA
225 de

A

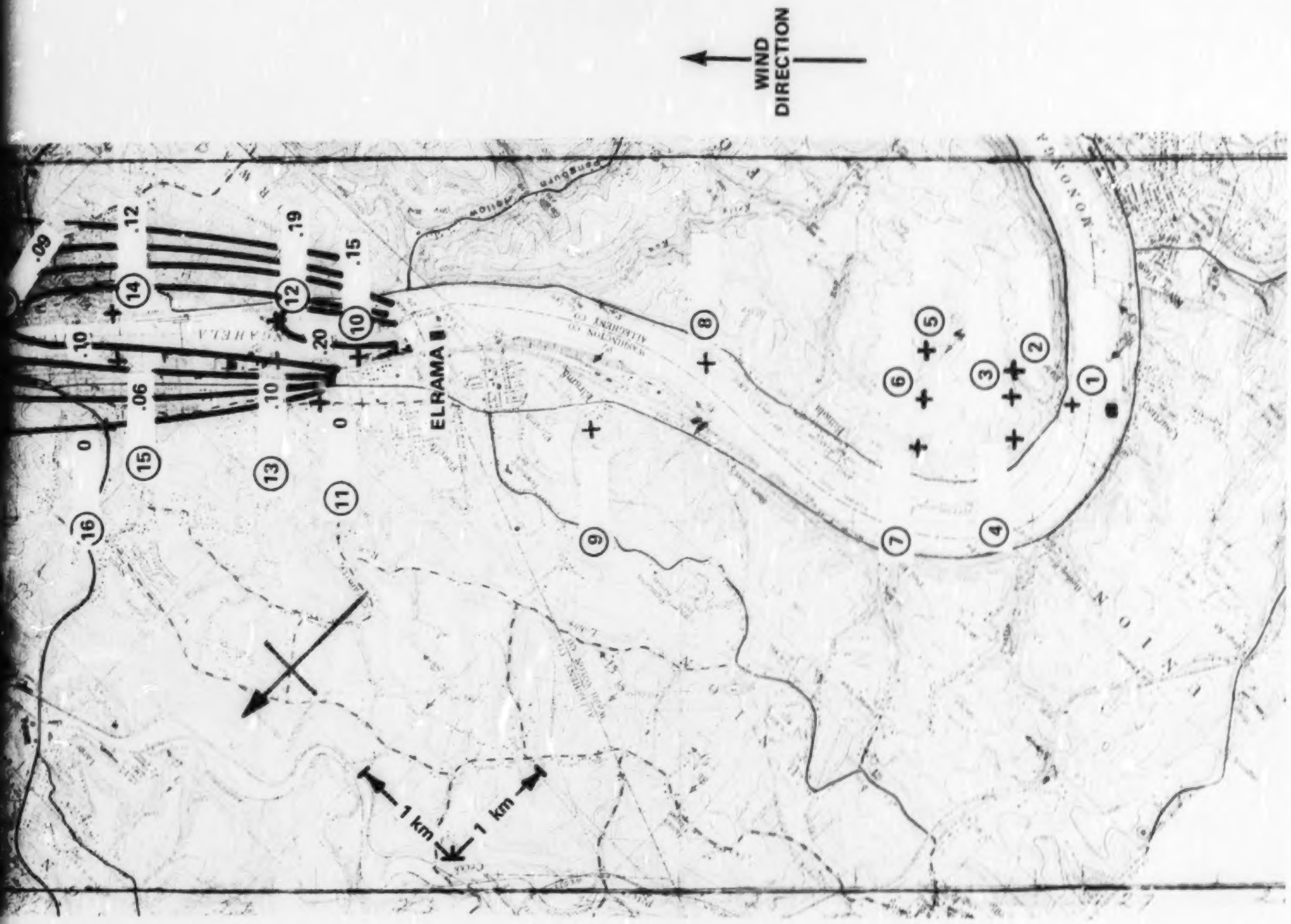

WIND DIRECTION
ELRAMA
MONONGAHELA
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
.09
.12
.19
.15
.10
.20
.06
.10
0
0
1 km
1 km

Figure 21 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
ELRAMA SIMULATED, NEUTRAL ATMOSPHERE
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 6 m/sec AT LIBERTY BOROUGH MONITOR

B

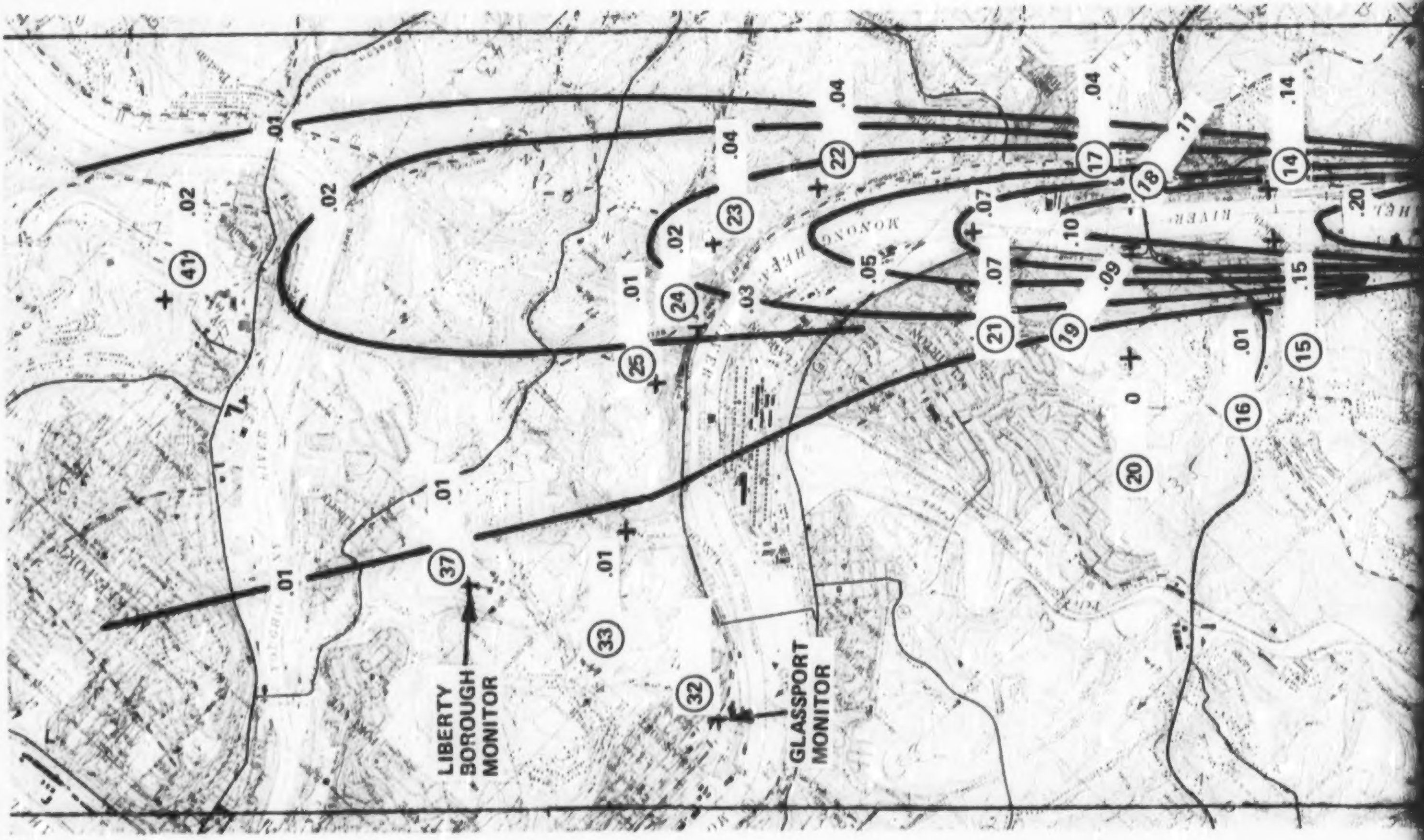

LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
MONONGAHELA RIVER
.01
.02
.03
.04
.05
.07
.09
.10
.11
.14
.15
.20
0
14
15
16
17
18
19
20
21
22
23
24
25
32
33
37
41

Figure 22 FULL
ELR
225

A

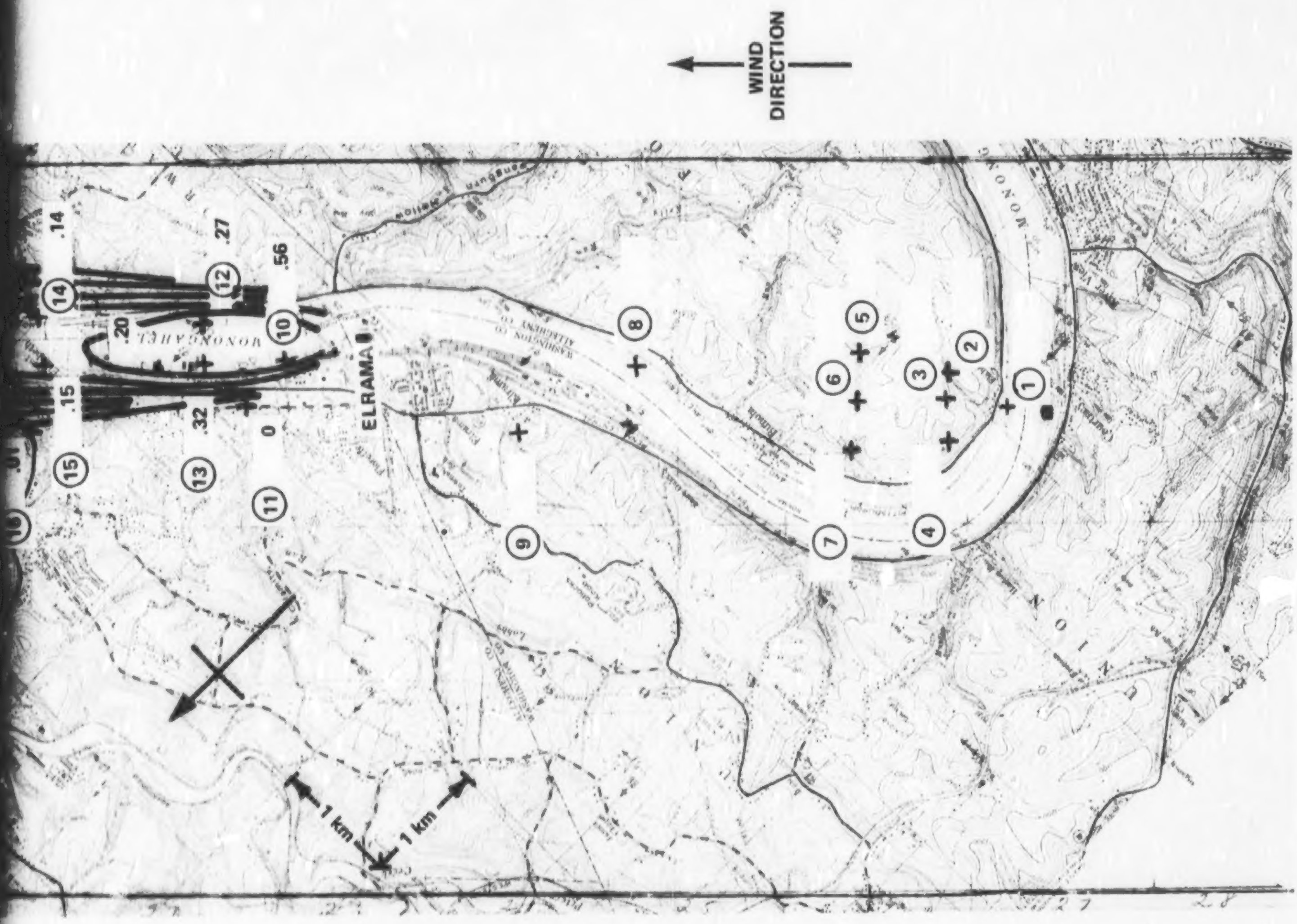
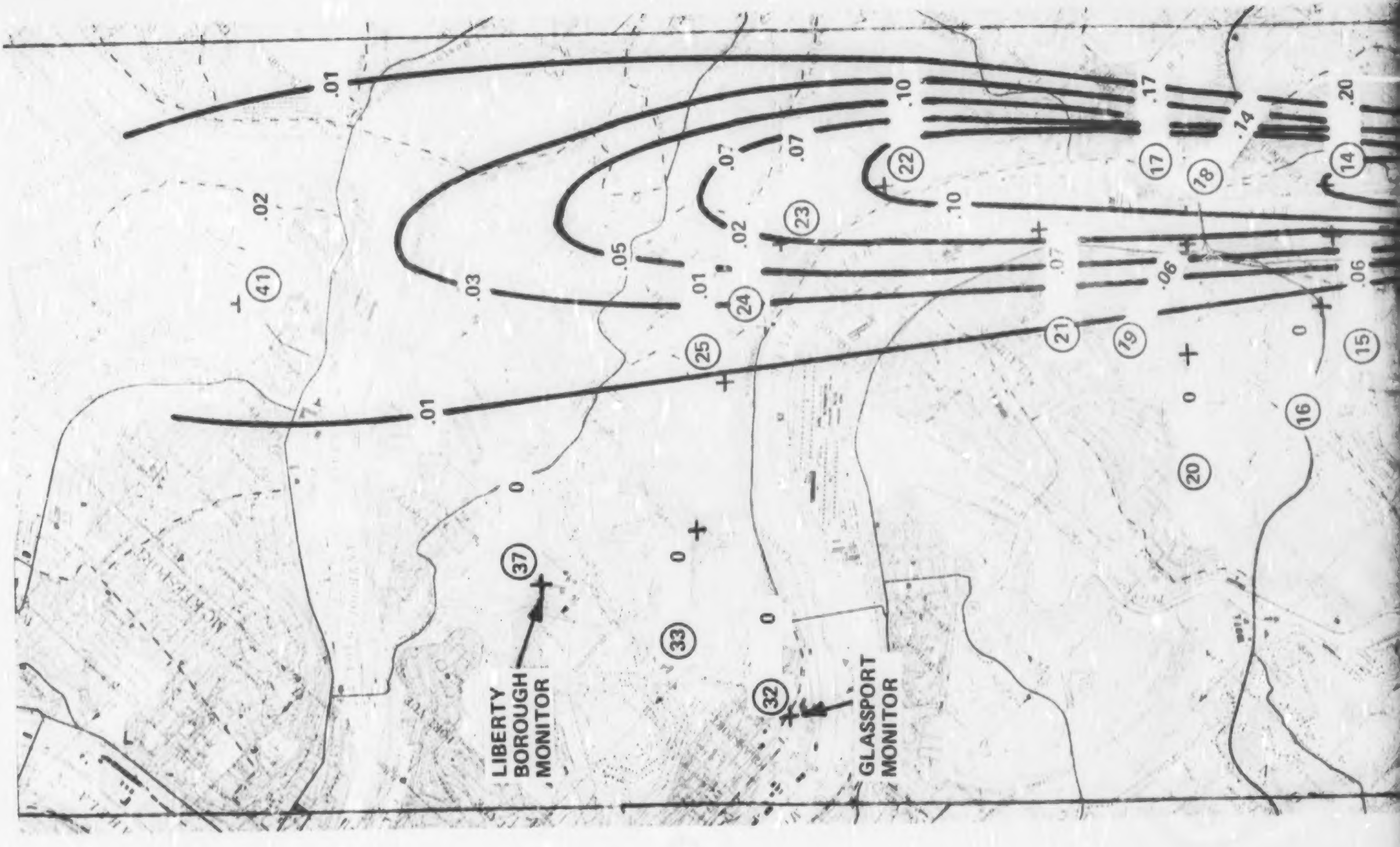

WIND DIRECTION
ELRAMA
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
.14
.27
.56
.20
.15
.32
0
.01
1 km
1 km

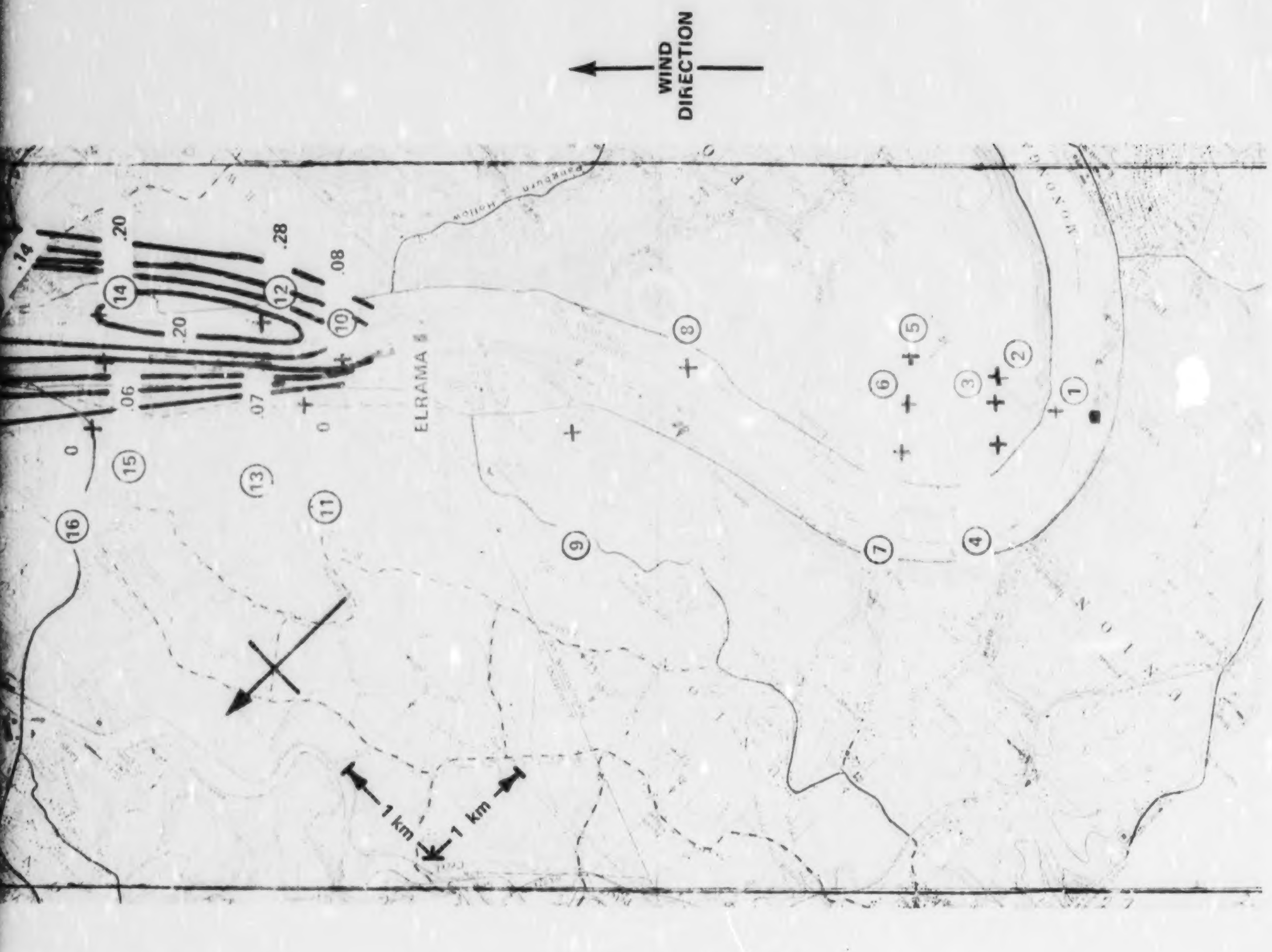
Figure 22 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCUALTED FROM MODEL TEST DATA ELRAMA SIMULATED, NEUTRAL ATMOSPHERE
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 22 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 8.8 m/sec AT LIBERTY BOROUGH MONITOR



.01
.02
.03
.05
.07
.07
.02
.01
.10
.10
.17
.14
.20
.07
.06
.06
0
0
0
0
0
.01
41
22
23
24
25
17
18
14
21
19
15
16
20
37
33
32
LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR

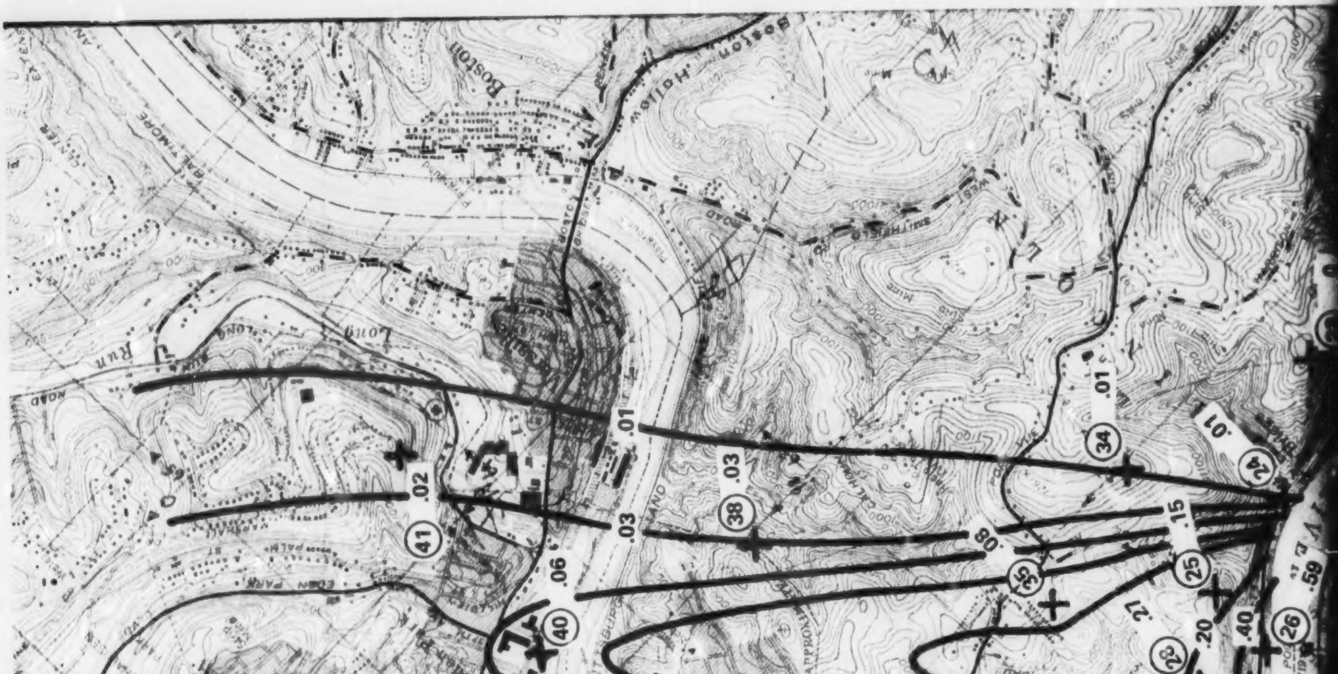
Figure 23 FULL
ELRA
225 d

A


WIND DIRECTION
ELRAMA
1 km
1 km
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫
⑬
⑭
⑮
⑯
.14
.20
.28
.08
.20
.06
.07
0
0

ure 23 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
ELRAMA SIMULATED, WITH INVERSION
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 9 m/sec AT LIBERTY BOROUGH MONITOR

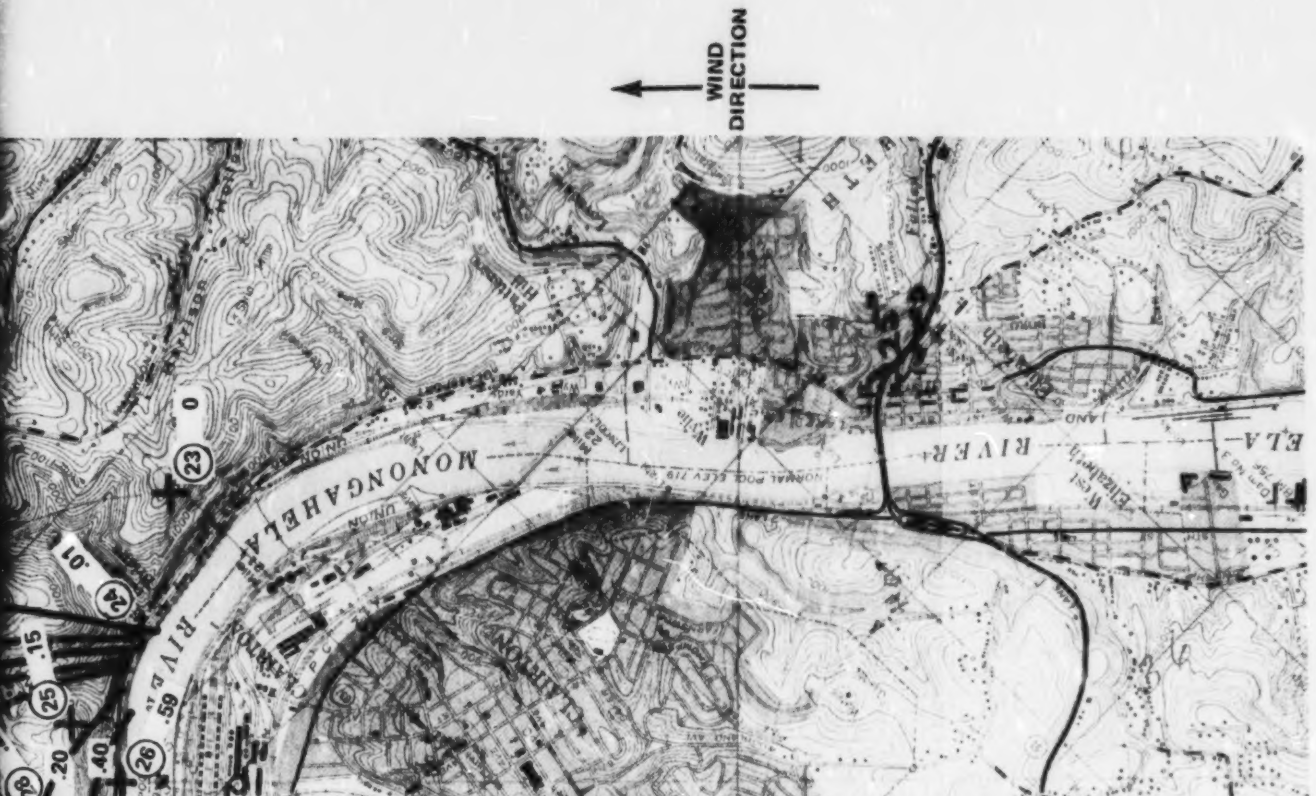
B



Boston
Boston Hollow
YOUGHIOGHENY
RIVER
McKEESPORT
Liberty
LIBERTY
BOROUGH
MONITOR
.01
.02
.03
.06
.08
.15
.07
.05
.10
.27
.20
.40
.59
.42
.11
0
.60
.04
34
24
41
38
35
25
40
28
26
36
29
27
33
39
37
42
32
30

Figure 24 FULL
CLAI
225 d

A


WIND DIRECTION
MONONGAHELA RIVER
CLAIRTON
CLAUS PLANT
GLASSPORT MONITOR
1 km
1 km
0
23
.01
24
.15
25
.59
.20
.40
26
28
.42
.10
29
27
.09
30
.04
31
0
32

gure 24 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
CLAIRTON (INCLUDING CLAUS) SIMULATED, NEUTRAL ATMOSPHERE
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 6 m/sec AT LIBERTY BOROUGH MONITOR

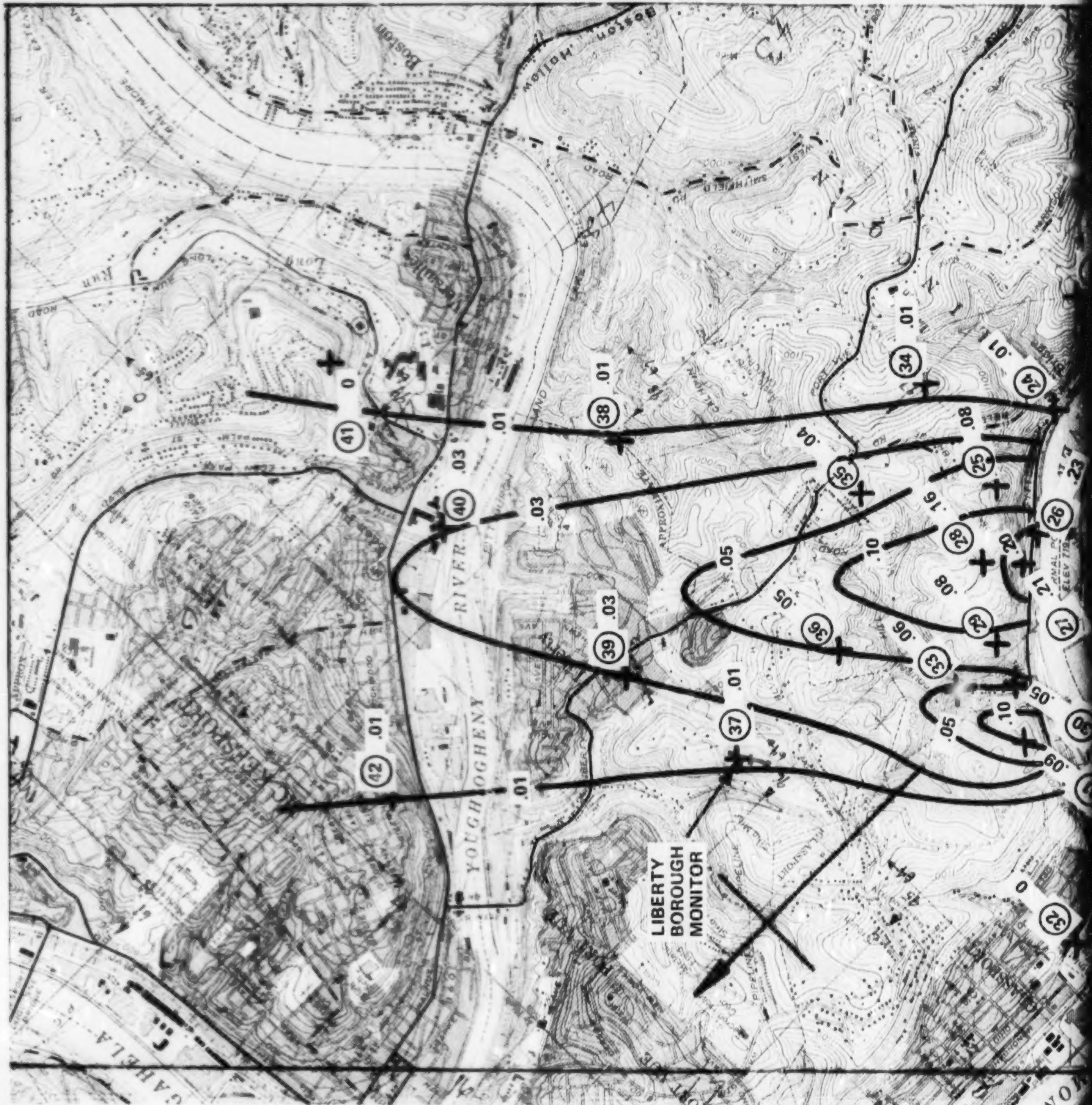
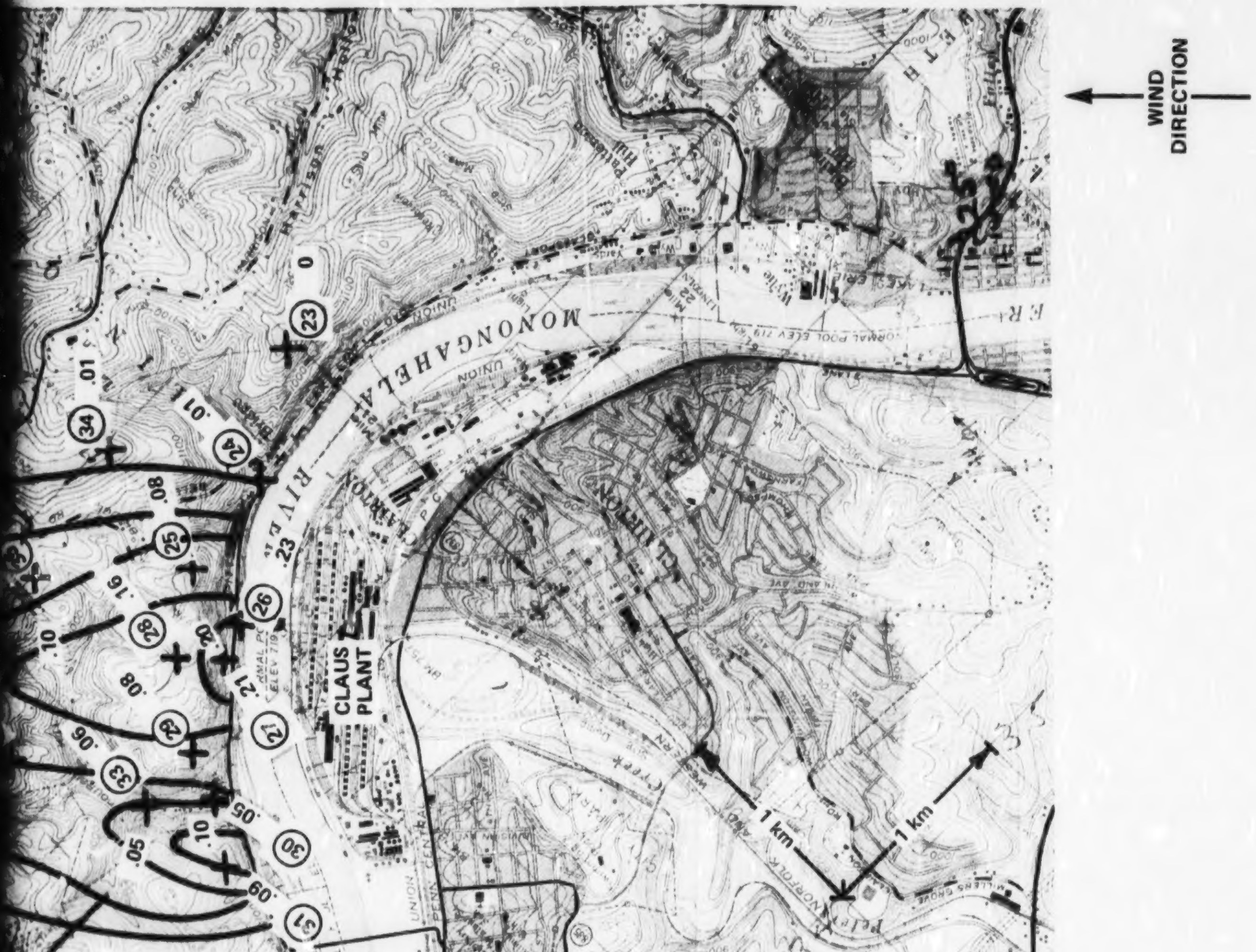

LIBERTY BOROUGH MONITOR
YOUGHIOGHENY
RIVER
Boston
Boston Hollow
41
38
40
39
42
37
36
35
34
33
32
30
28
26
25
24
23
22
21
0
.01
.03
.04
.05
.06
.08
.10
.16
.20
.21
.23
.60

Figure 25 FULL-SCALE SO-
CLAIRTON (INC
225 deg WIND, FU
FU

A


WIND DIRECTION
MONONGAHELA RIVER
CLAIRTON
CLAUS PLANT
GLASSPORT MONITOR
1 km
1 km
0
23
.01
34
24
.08
25
.23
.16
26
.10
28
.20
.08
.21
21
.06
29
33
.05
.10
.05
30
.09
31
0
32

ure 25 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) -- CALCULATED FROM MODEL TEST DATA
CLAIRTON (INCLUDING CLAUS) SIMULATED, NEUTRAL ATMOSPHERE
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 22 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 8.8 m/sec AT LIBERTY BOROUGH MONITOR

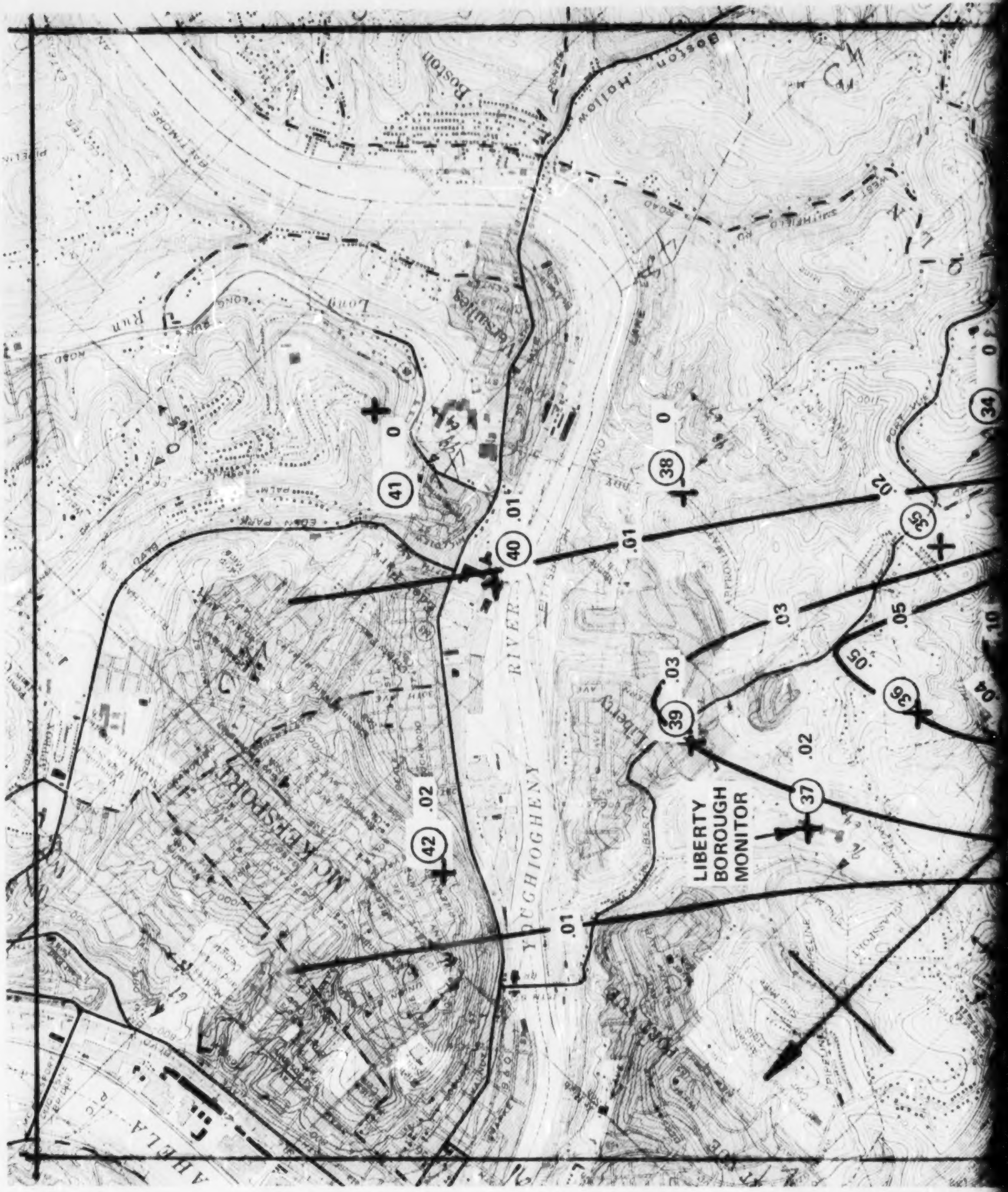
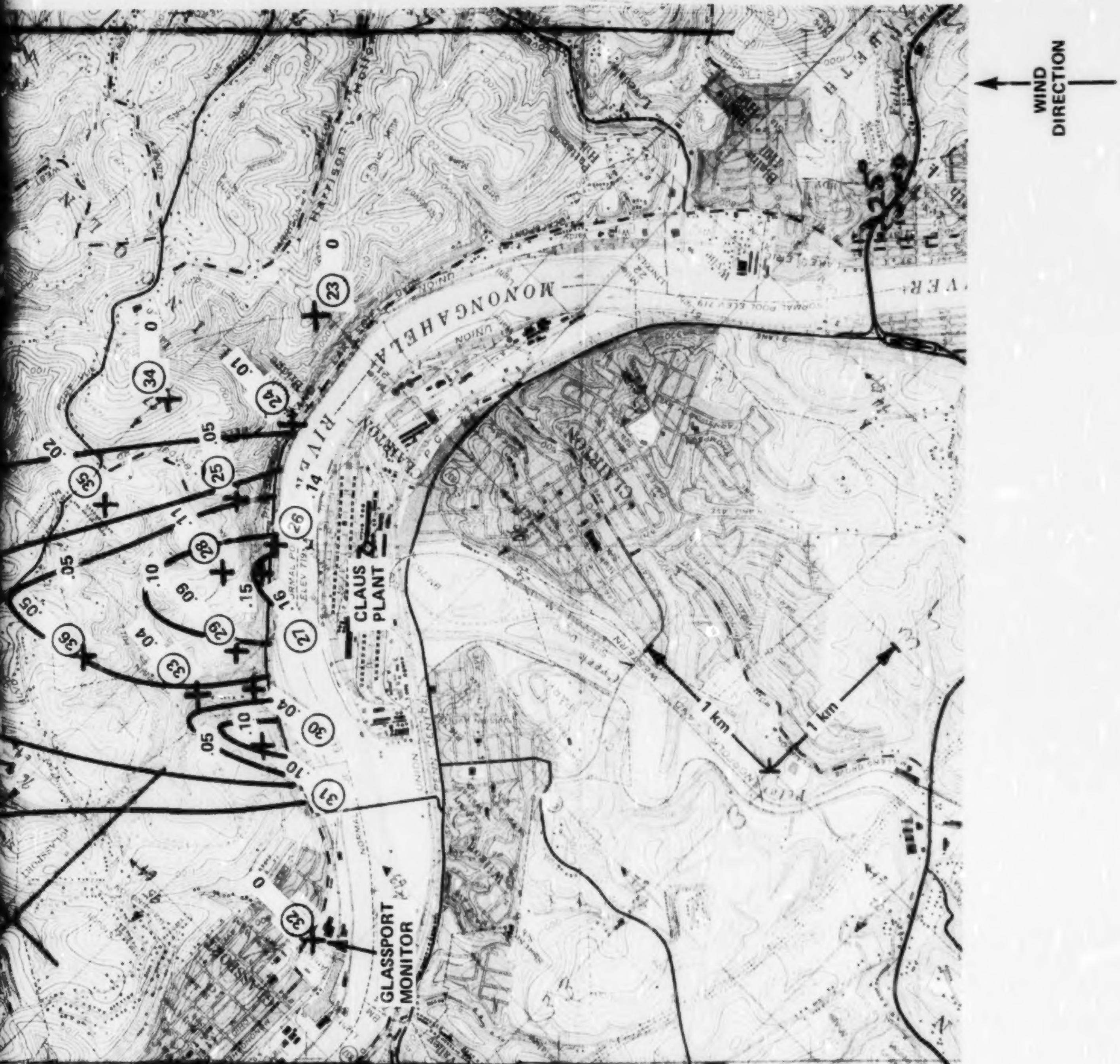

LIBERTY BOROUGH MONITOR
McKEESPORT
YOUGHIOGHENY
RIVER
Boston
Boston Hollow
Long Run
Liberty
34
35
36
37
38
39
40
41
42
0
0
0
.01
.01
.01
.02
.02
.02
.03
.03
.04
.05
.05
.10

Figure 26 FULL-
CLAIR
225 de

A


WIND DIRECTION
MONONGAHELA RIVER
CLAIRTON
CLAUS PLANT
GLASSPORT MONITOR
1 km
1 km
23
24
25
26
27
28
29
30
31
32
33
34
35
36
0
.01
.02
.04
.05
.09
.10
.11
.14
.15
.16

igure 26 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
CLAIRTON (INCLUDING CLAUS) SIMULATED, WITH INVERSION
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 9 m/sec AT LIBERTY BOROUGH MONITOR

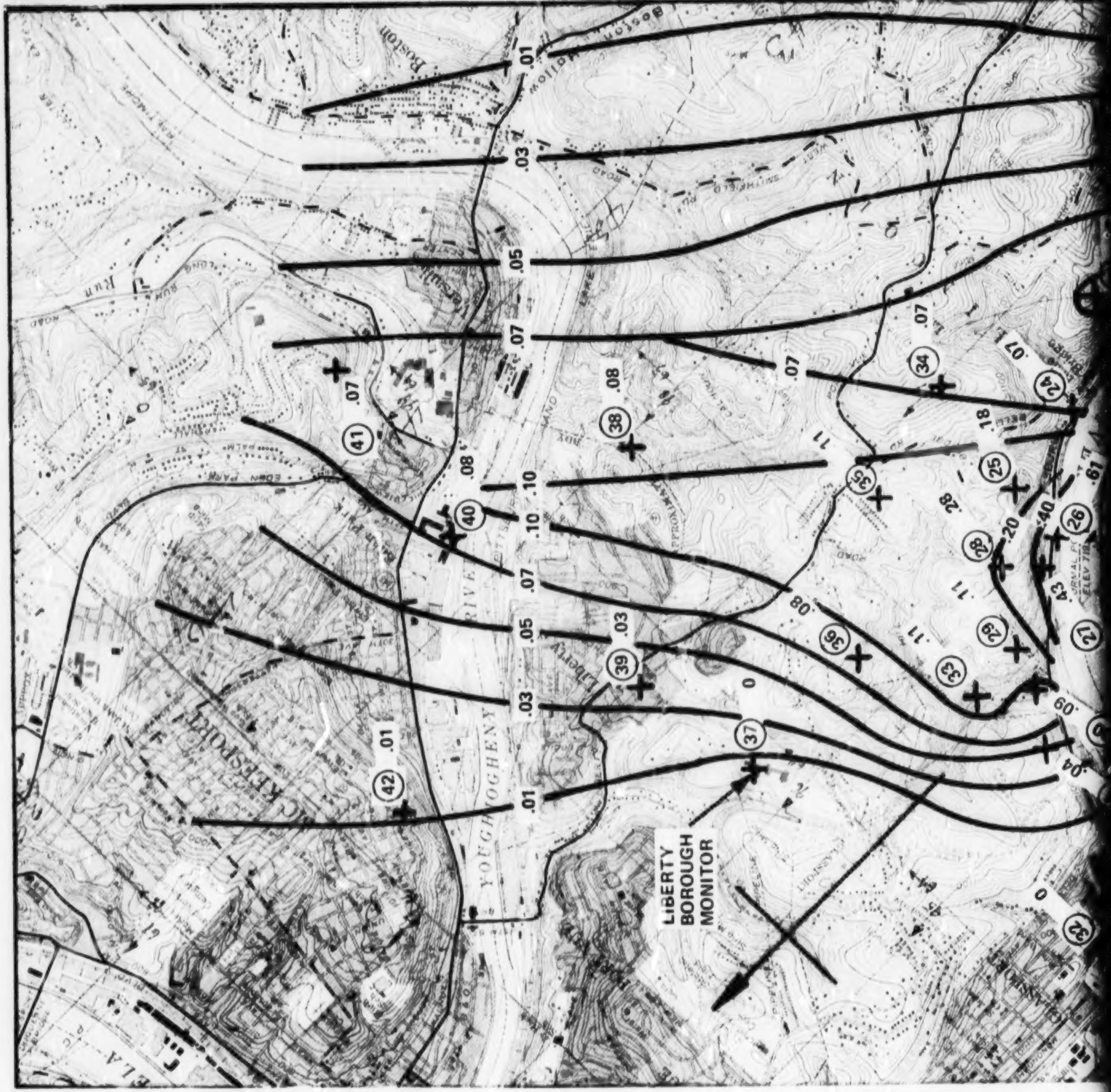
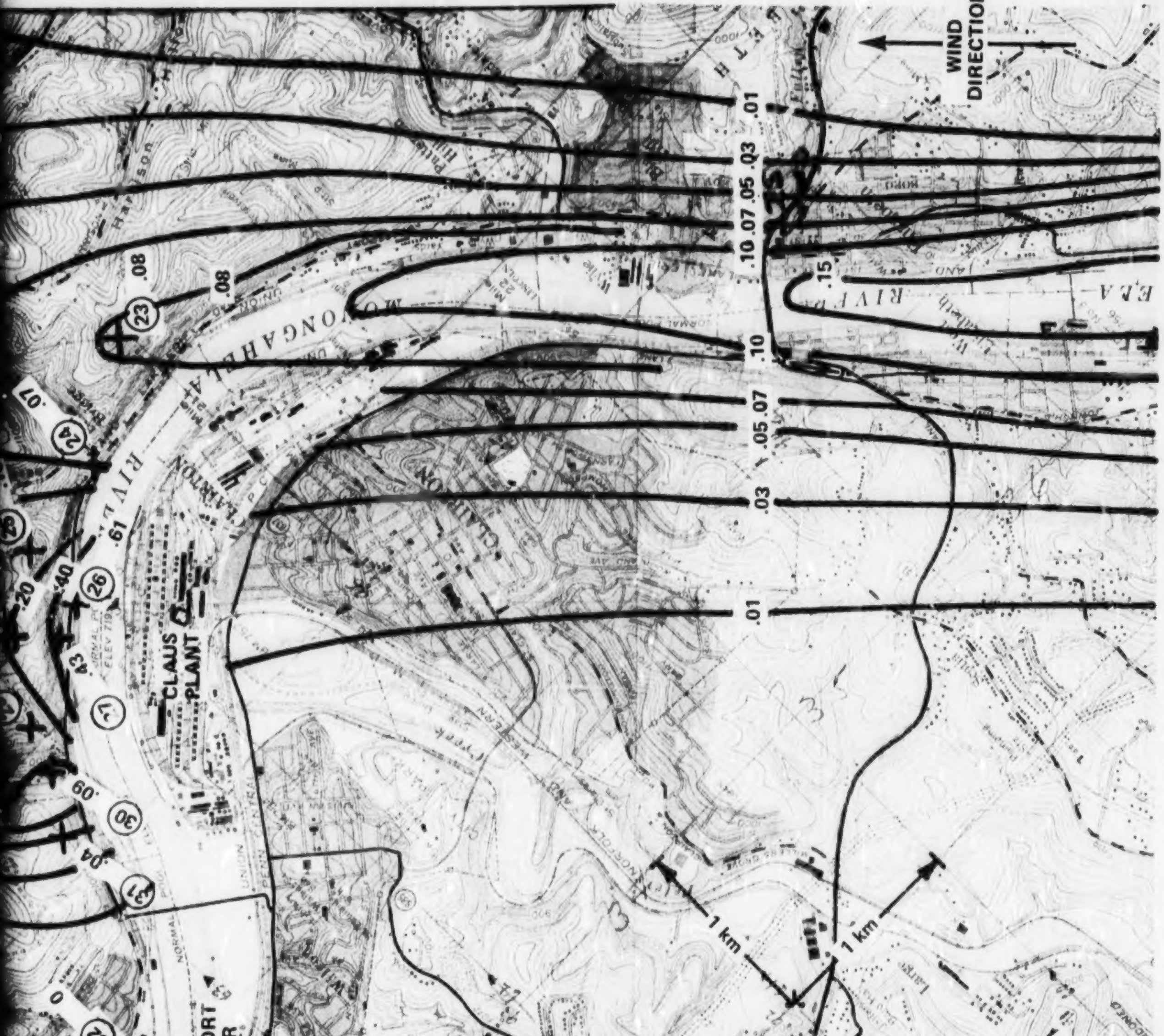

.01
.03
.05
.07
.07
.07
.07
.08
.08
.10
.10
.07
.05
.03
.03
.01
.01
0
.11
.18
.28
.20
.40
.43
.11
.11
.08
.09
.04
.19
0
㉔
㉕
㉖
㉗
㉘
㉙
㉜
㉝
㉞
㉟
㊱
㊲
㊳
㊴
㊵
㊶
㊷
LIBERTY
BOROUGH
MONITOR
YOUGHIOGHENY
RIVER
McKEESPORT
Boston

Figure 27 FULL
MITC
225 d

A


WIND DIRECTION
.01
.03
.05
.07
.10
.15
.08
.08
.10
.07
.05
.03
.01
.07
.61
.40
.20
.43
.60
.04
0
MONONGAHELA
RIVER
CLAIRTON
CLAUS PLANT
GLASSPORT MONITOR
1 km
1 km
23
24
26
30
31
32

27 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
MITCHELL, ELRAMA, CLAIRTON (INCLUDING CLAUS) SIMULATED, NEUTRAL ATMOSPHERE
225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 6 m/sec AT LIBERTY BOROUGH MONITOR

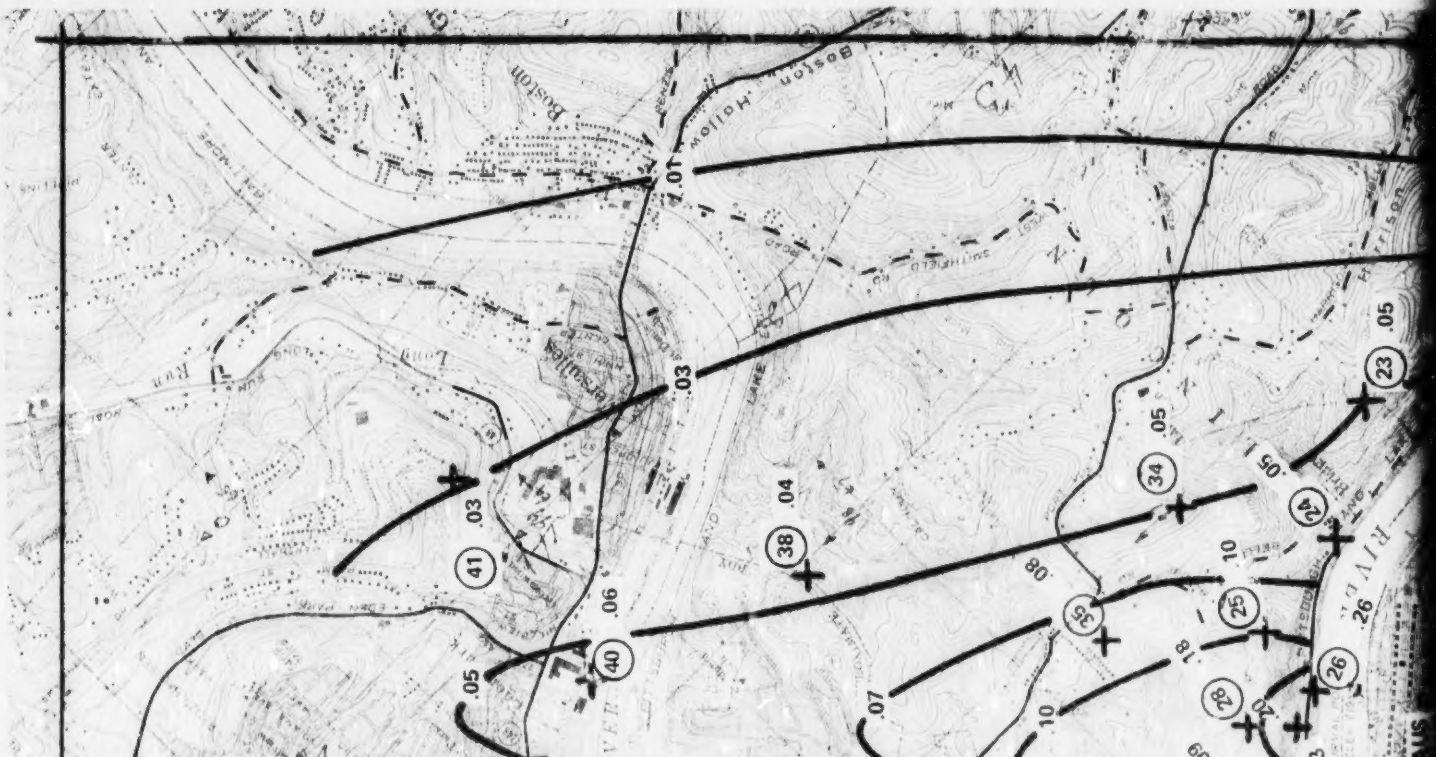
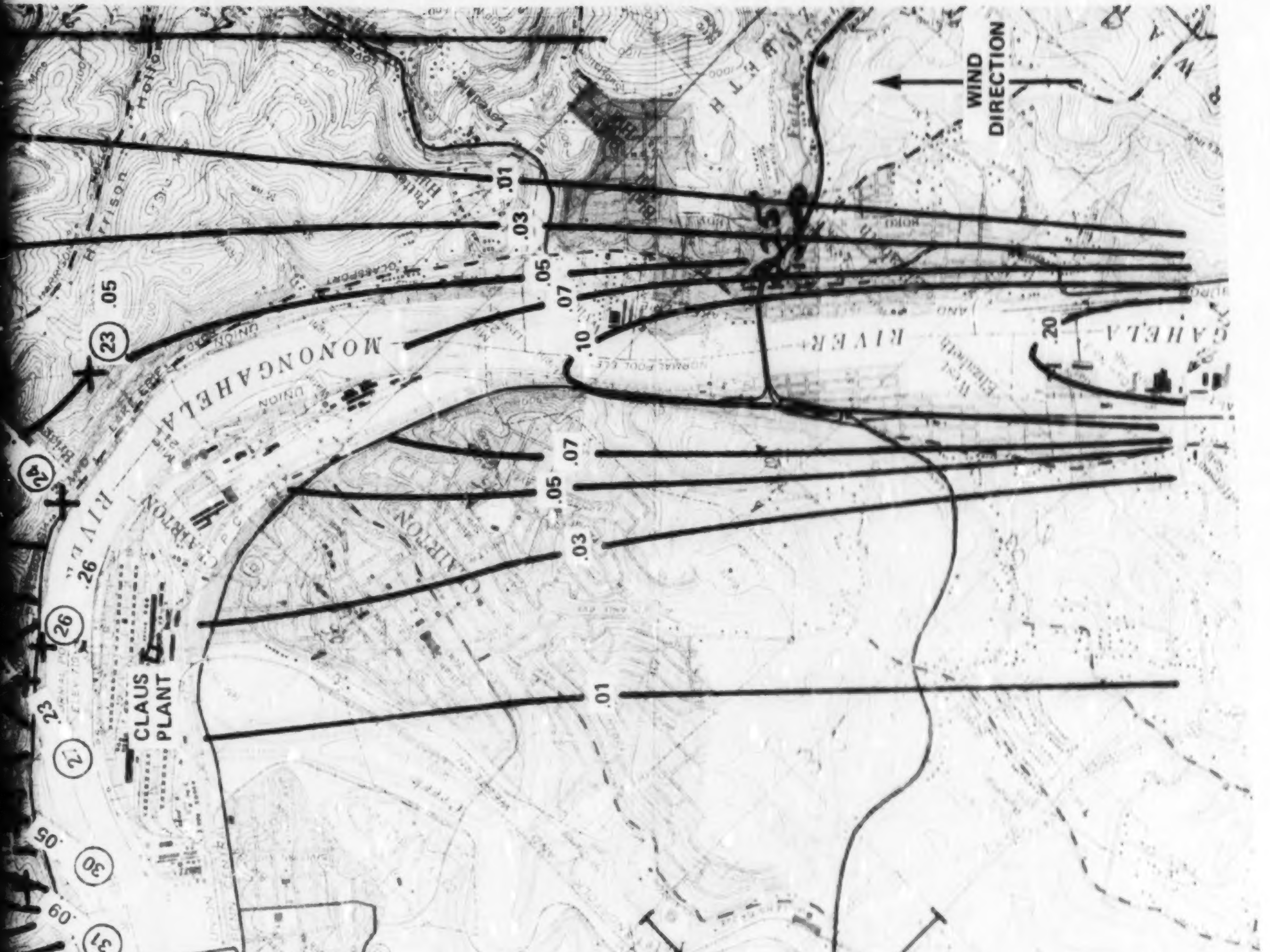

LIBERTY
BOROUGH
MONITOR
41
42
40
39
38
37
36
35
34
33
32
31
30
29
28
26
25
24
23
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.18
.20
.23
.26
0
Boston
Boston Hollow
Long Run
McKEESPORT
YOUGHIOGHENY
RIVER
PORT VUE
CLAIRTON
Harrison

Figure 28 FULL-
MITCH
225 de

A


WIND DIRECTION
.01
.03
.05
.07
.10
.20
.07
.05
.03
.01
MONONGAHELA
RIVER
CLAIRTON
CLAUS PLANT
GLASSPORT MONITOR
1 km
1 km
.05
23
24
26
26
.23
27
.05
30
.09
31
32

28 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA MITCHELL, ELRAMA, CLAIRTON (INCLUDING CLAUS) SIMULATED, NEUTRAL ATMOSPHERE 225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 22 m/sec AT 2926 m ABOVE RIVER FULL-SCALE REFERENCE VELOCITY = 8.8 m/sec AT LIBERTY BOROUGH MONITOR

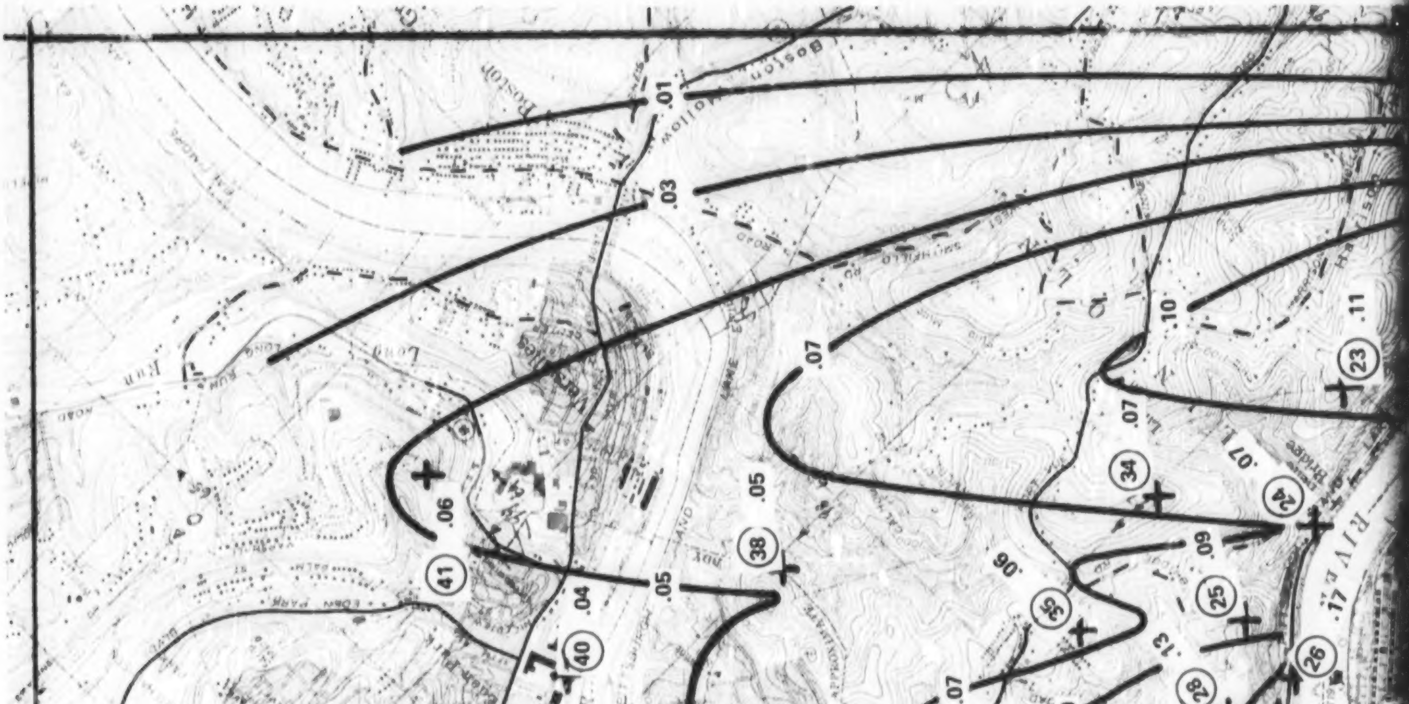
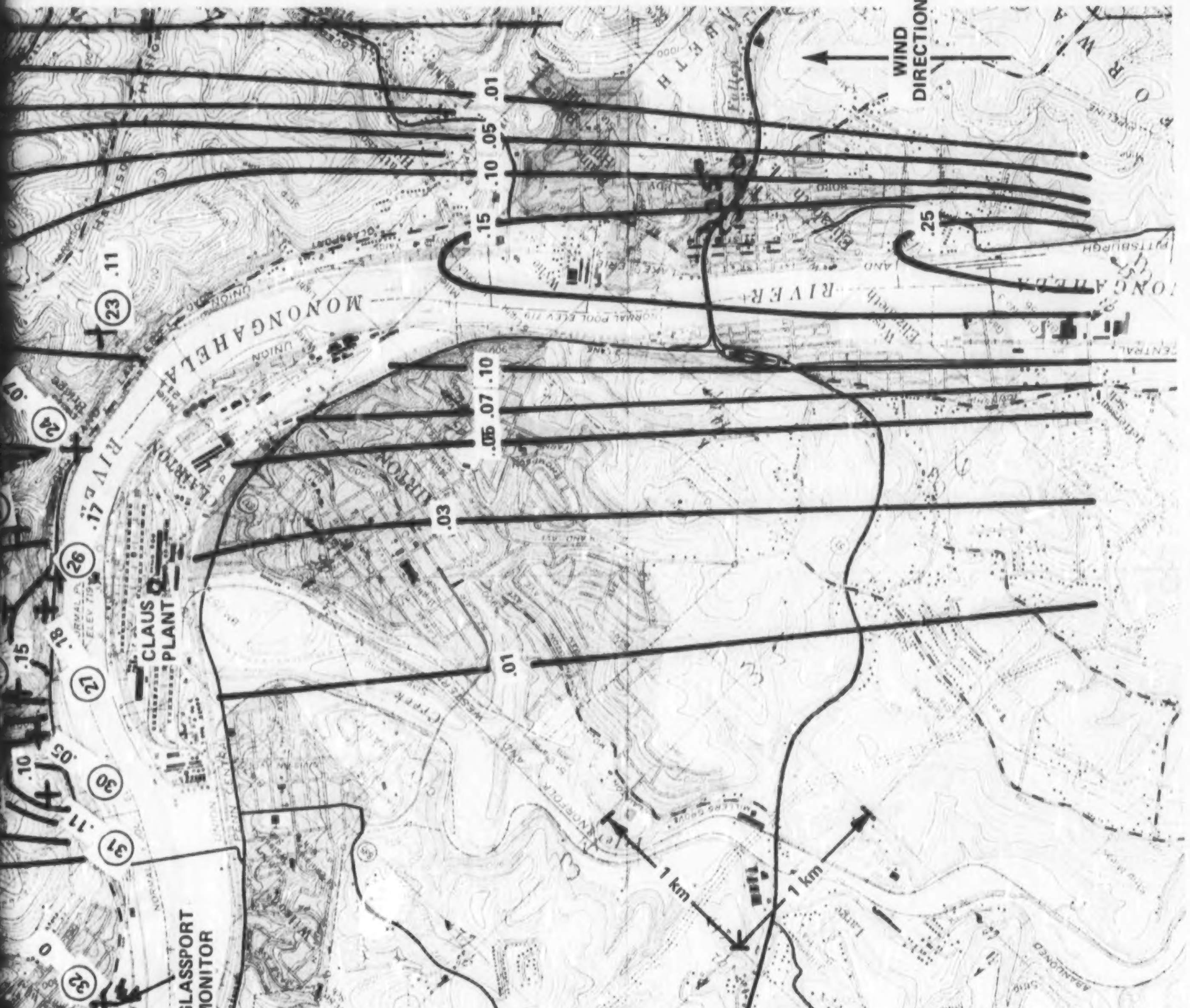

LIBERTY BOROUGH MONITOR
McKEESPORT
YOUGHIOGHENY RIVER
Boston
.01
.02
.03
.04
.05
.06
.07
.09
.10
.11
.13
.15
.17
.18
0
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42

Figure 29 FUL
MITC
225

A


WIND DIRECTION
.01
.05
.10
.15
.25
.11
.07
.17
.18
.15
.10
.05
.11
0
.10
.07
.05
.03
.01
23
24
26
27
30
31
32
CLAUS PLANT
GLASSPORT MONITOR
1 km
1 km
MONONGAHELA
RIVER
CLAIRTON

igure 29 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA MITCHELL, ELRAMA, CLAIRTON (INCLUDING CLAUS) SIMULATED, WITH INVERSION 225 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER FULL-SCALE REFERENCE VELOCITY = 9 m/sec AT LIBERTY BOROUGH MONITOR

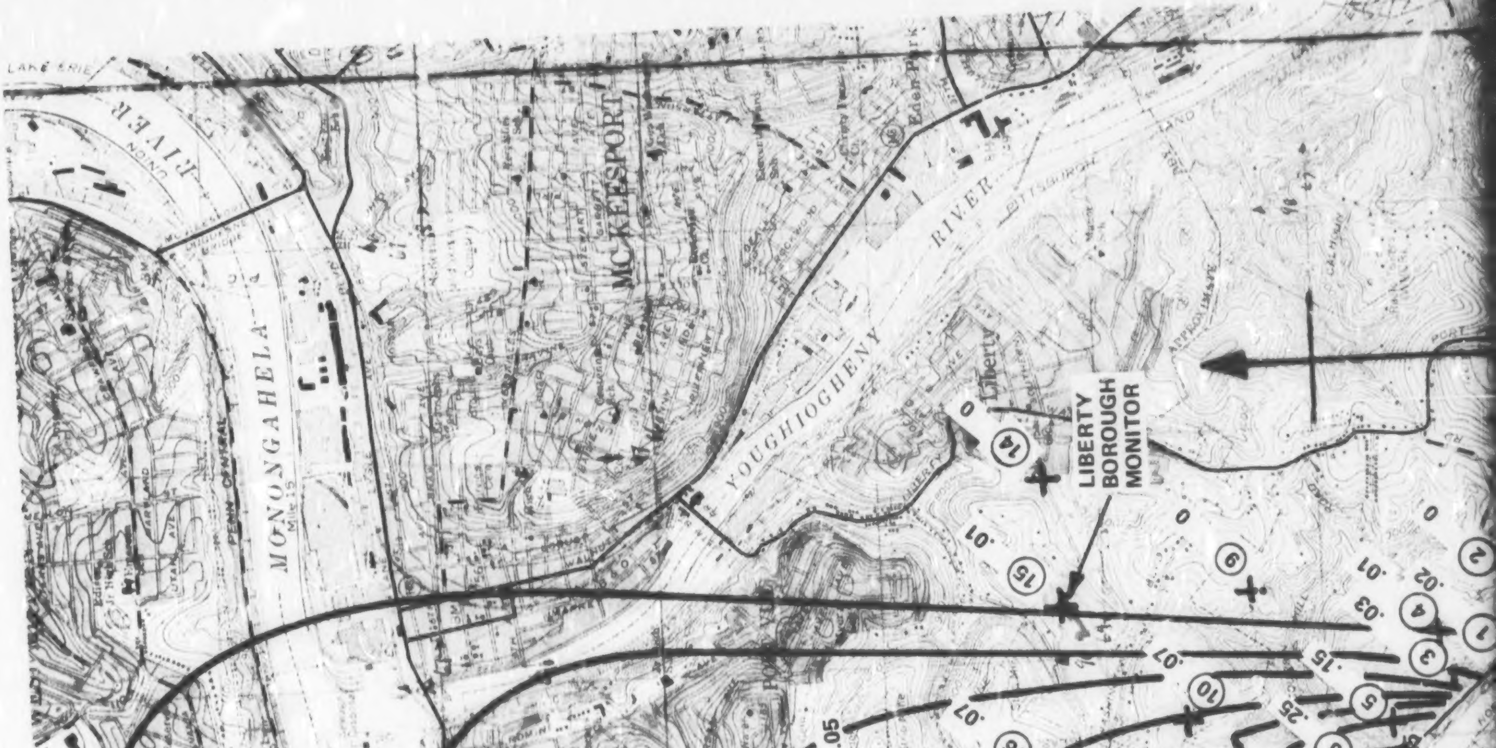

LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
MONONGAHELA
YOUGHIOGHENY RIVER
MC KEESPORT
PORT VUE
DRAVOSBURG
Liberty
LAKE ERIE
RIVER
0
.01
.02
.03
.05
.07
.10
.11
.12
.15
.16
.25
.35
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Figure 30

A

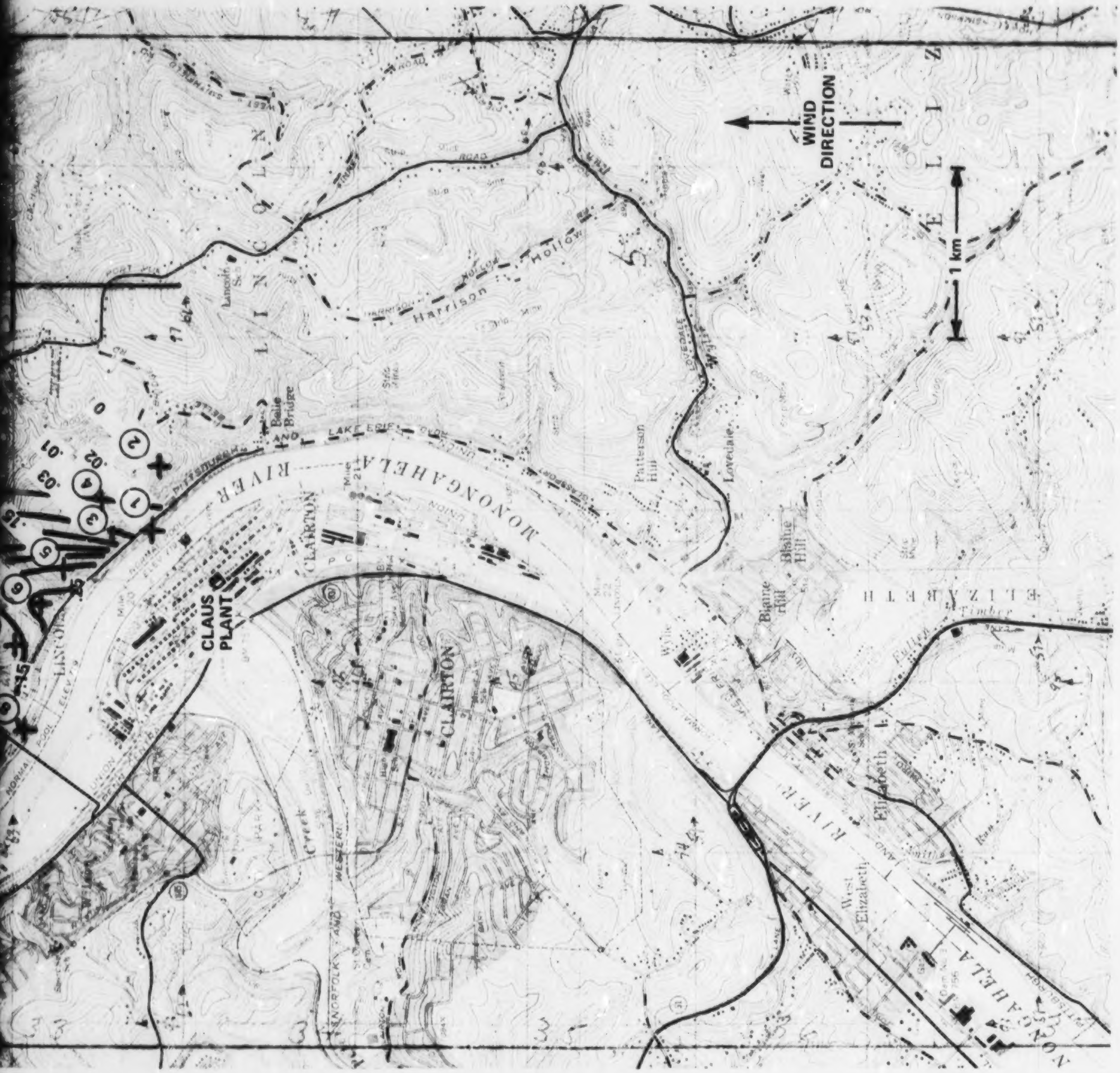

WIND DIRECTION
1 km
CLAUS PLANT
0
.01
.02
.03
.15
.15
①
②
③
④
⑤
⑥
⑧
MONONGAHELA RIVER
CLAIRTON
Patterson Hill
Lovedale
Blaine Hill
ELIZABETH
West Elizabeth
Harrison Hollow
LINCOLN
Lake Erie

Figure 30 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
CLAIRTON (INCLUDING CLAUS) SIMULATED, NEUTRAL ATMOSPHERE
180 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 6 m/sec AT LIBERTY BOROUGH MONITOR

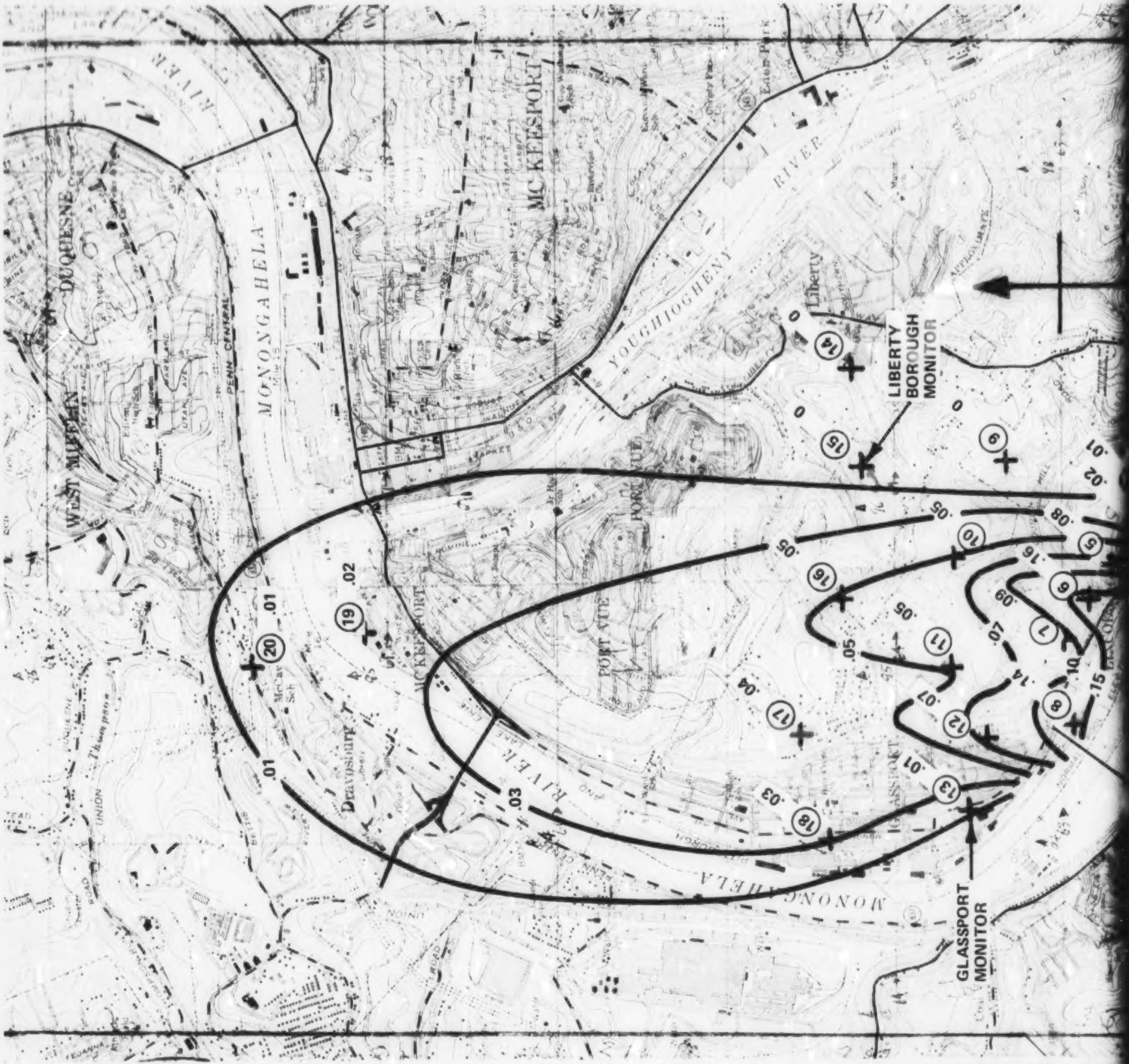

RIVER
DUQUESNE
WEST MIFFLIN
MONONGAHELA
PENN CENTRAL
MC KEESPORT
YOUGHIOGHENY RIVER
Liberty
LIBERTY BOROUGH MONITOR
PORT VUE
Dravosburg
GLASSPORT
GLASSPORT MONITOR
MONONGAHELA
RIVER
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
0
.01
.02
.03
.04
.05
.07
.08
.09
.10
.14
.15
.16

Figure 31 FUL
CLA
180

A

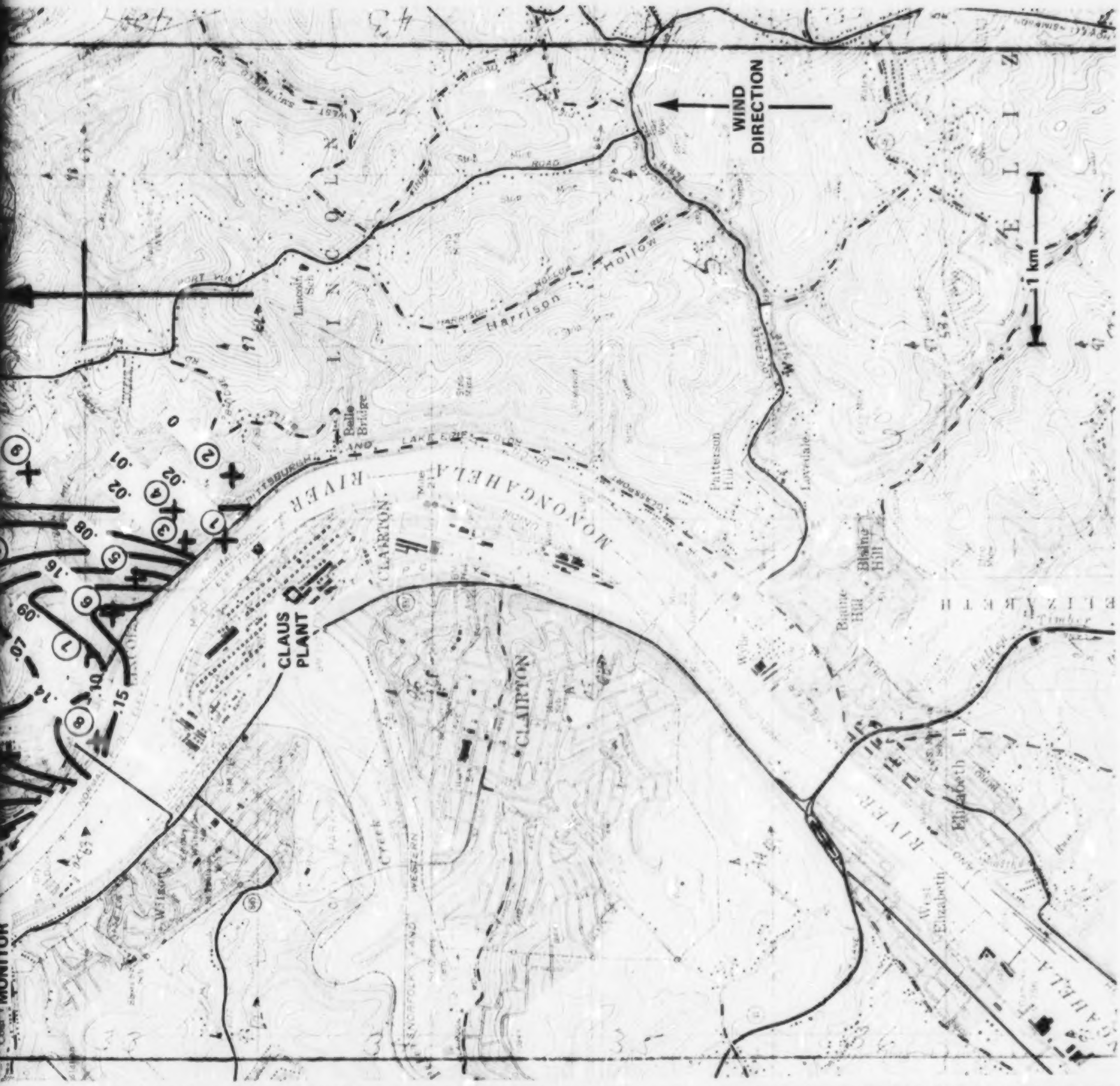

WIND DIRECTION
1 km
CLAUS PLANT
MONITOR
0
.01
.02
.02
.08
.16
.09
.07
.10
.14
.15
①
②
③
④
⑤
⑥
⑦
⑧
⑨
Lincoln Sch
Harrison Hollow
Belle Bridge
MONONGAHELA RIVER
CLAIRTON
CLAIRTON
Patterson Hill
Lovedale
Blaine Hill
ELIZABETH
West Elizabeth
Elizabeth
Wilson
Creek

Figure 31 FULL-SCALE SO$_2$ GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA CLAIRTON (INCLUDING CLAUS) SIMULATED, NEUTRAL ATMOSPHERE 180 deg WIND, FULL-SCALE REFERENCE VELOCITY = 22 m/sec AT 2926 m ABOVE RIVER FULL-SCALE REFERENCE VELOCITY = 8.8 m/sec AT LIBERTY BOROUGH MONITOR

B

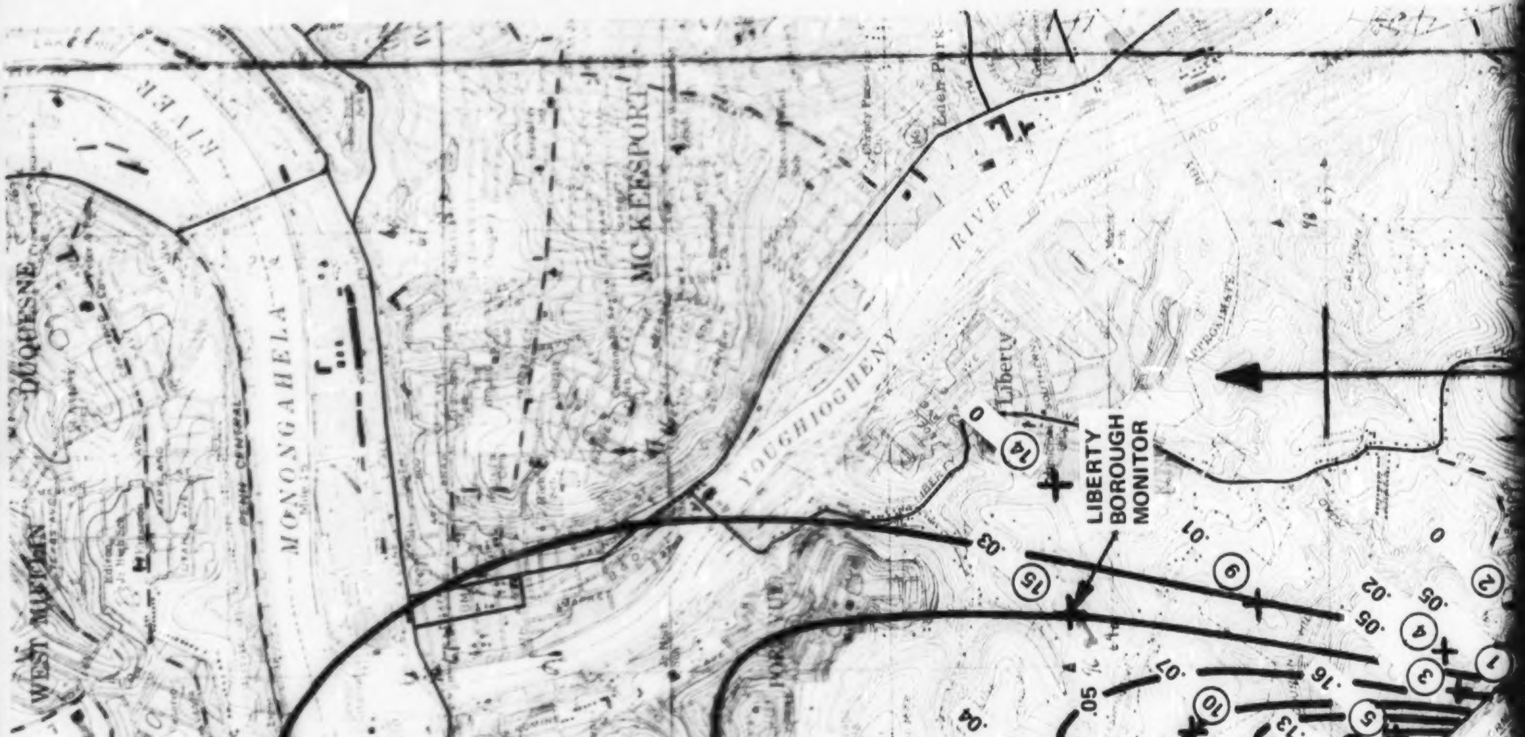

DUQUESNE
WEST MIFFLIN
MONONGAHELA RIVER
MC KEESPORT
YOUGHIOGHENY RIVER
Liberty
Eden Park
Port Vue
Dravosburg
Glassport
LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
.01
.02
.03
.04
.05
.07
.09
.10
.13
.15
.16
.22

Figure 32 FULL-S
CLAIRT
180 deg

A

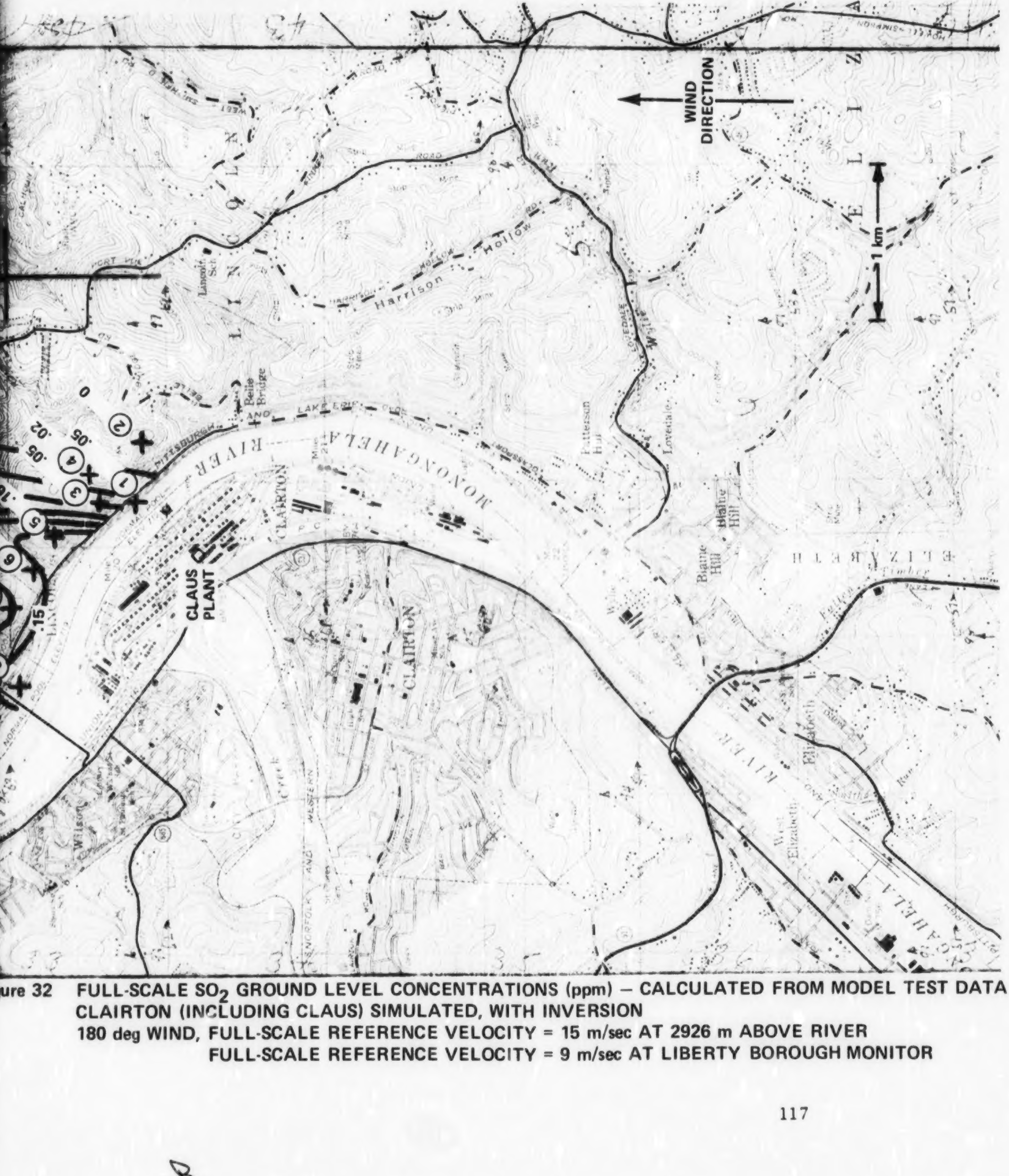

WIND DIRECTION
1 km
CLAUS PLANT
MONONGAHELA RIVER
RIVER
CLAIRTON
Harrison Hollow
Lincoln Sch
Belle Bridge
Patterson Hill
Lovedale
Blaine Hill
ELIZABETH
West Elizabeth
Wilson
Creek
0
.02
.05
.05
.16
.15
1
2
3
4
5
6

Figure 32 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA CLAIRTON (INCLUDING CLAUS) SIMULATED, WITH INVERSION
180 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 9 m/sec AT LIBERTY BOROUGH MONITOR

B

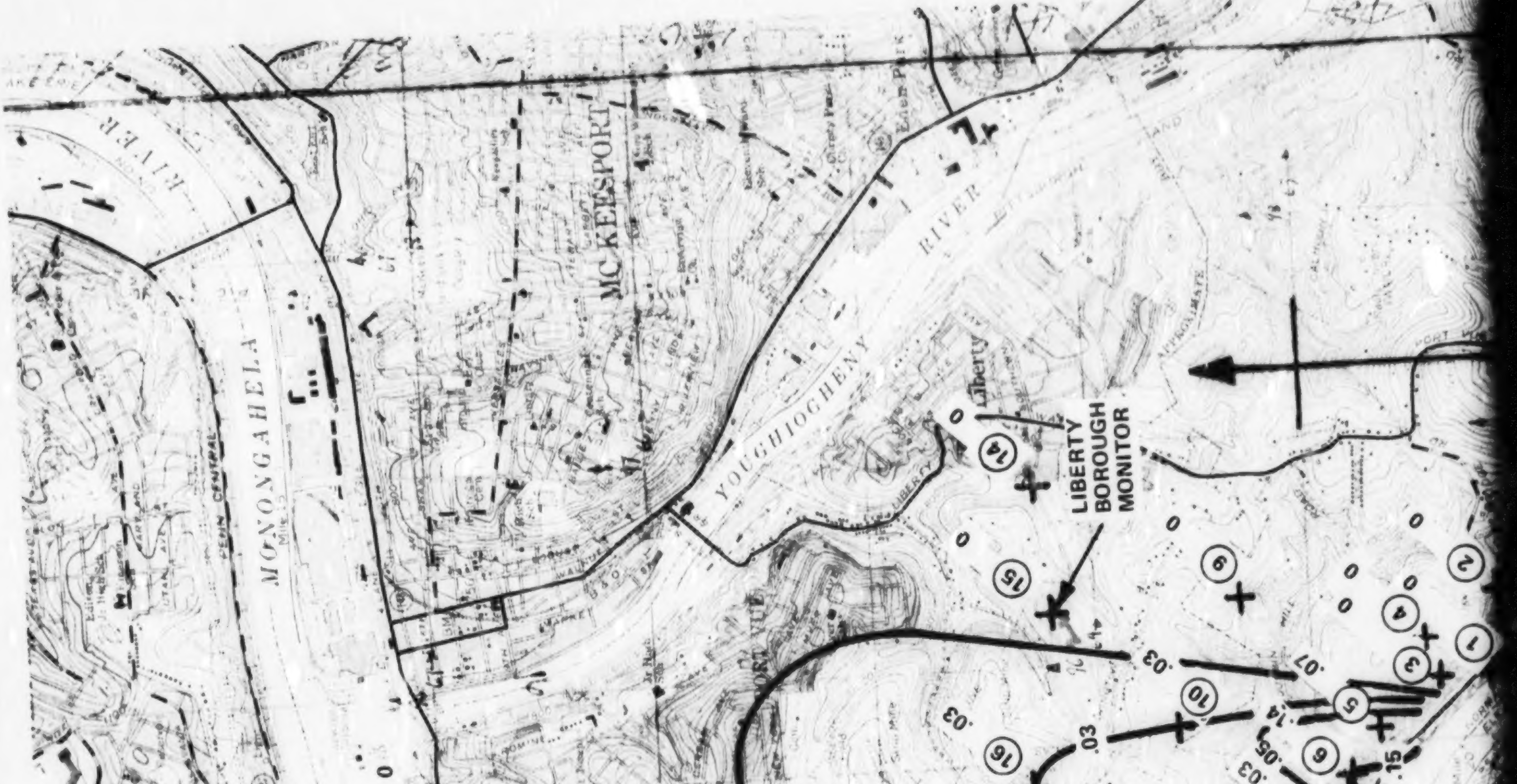
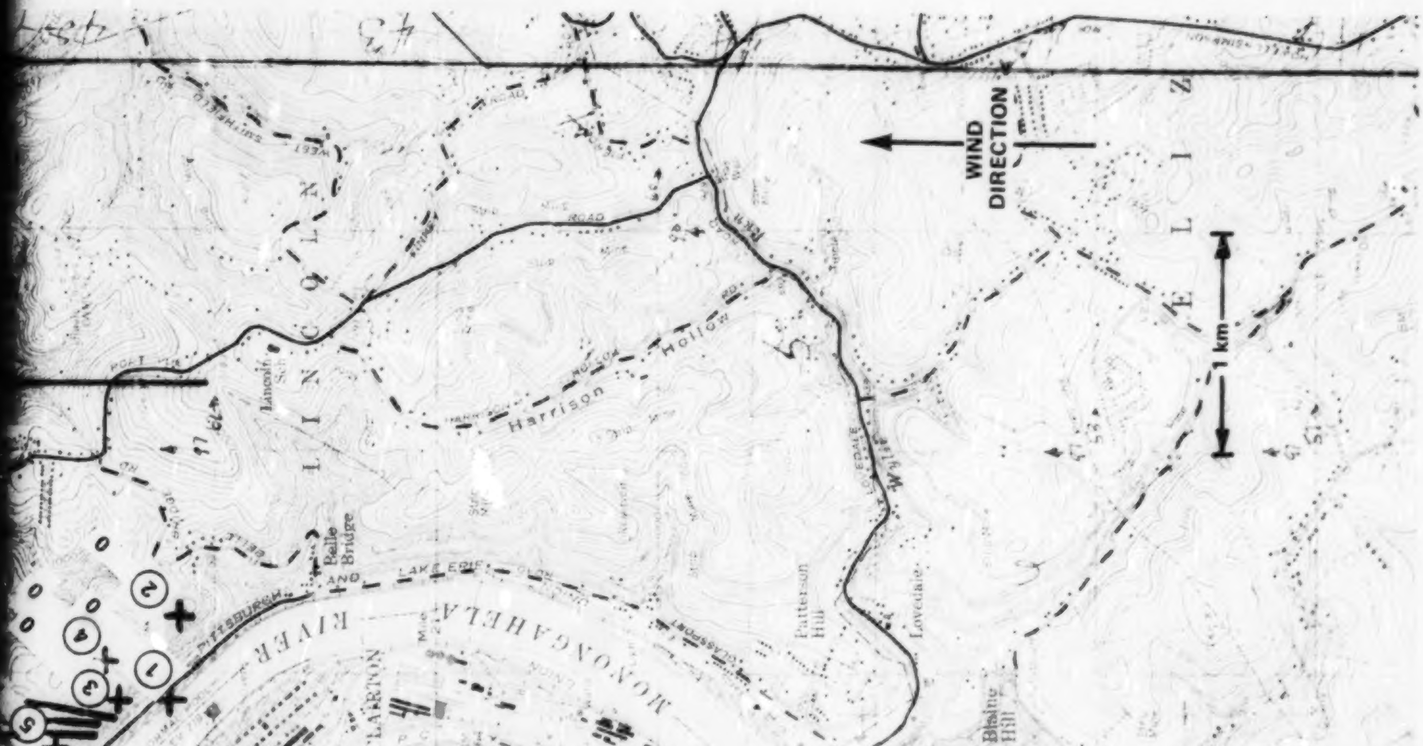

MONONGAHELA RIVER
YOUGHIOGHENY RIVER
MC KEESPORT
PORT VUE
GLASSPORT
LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
Dravosburg
Liberty
.01
.03
.05
.07
.14
.15
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

Figure 33 FUL
CLA
180

A


WIND DIRECTION
1 km
CLAUS PLANT
CLAIRTON
MONONGAHELA RIVER
Lincoln
Harrison Hollow
Belle Bridge
Patterson Hill
Lovedale
Blaine Hill
Blaine Hill
ELIZABETH
West Elizabeth
Elizabeth
.15
0
1
2
3
4
5

gure 33 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
CLAUS PLANT SIMULATED, NEUTRAL ATMOSPHERE
180 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 6 m/sec AT LIBERTY BOROUGH MONITOR

B

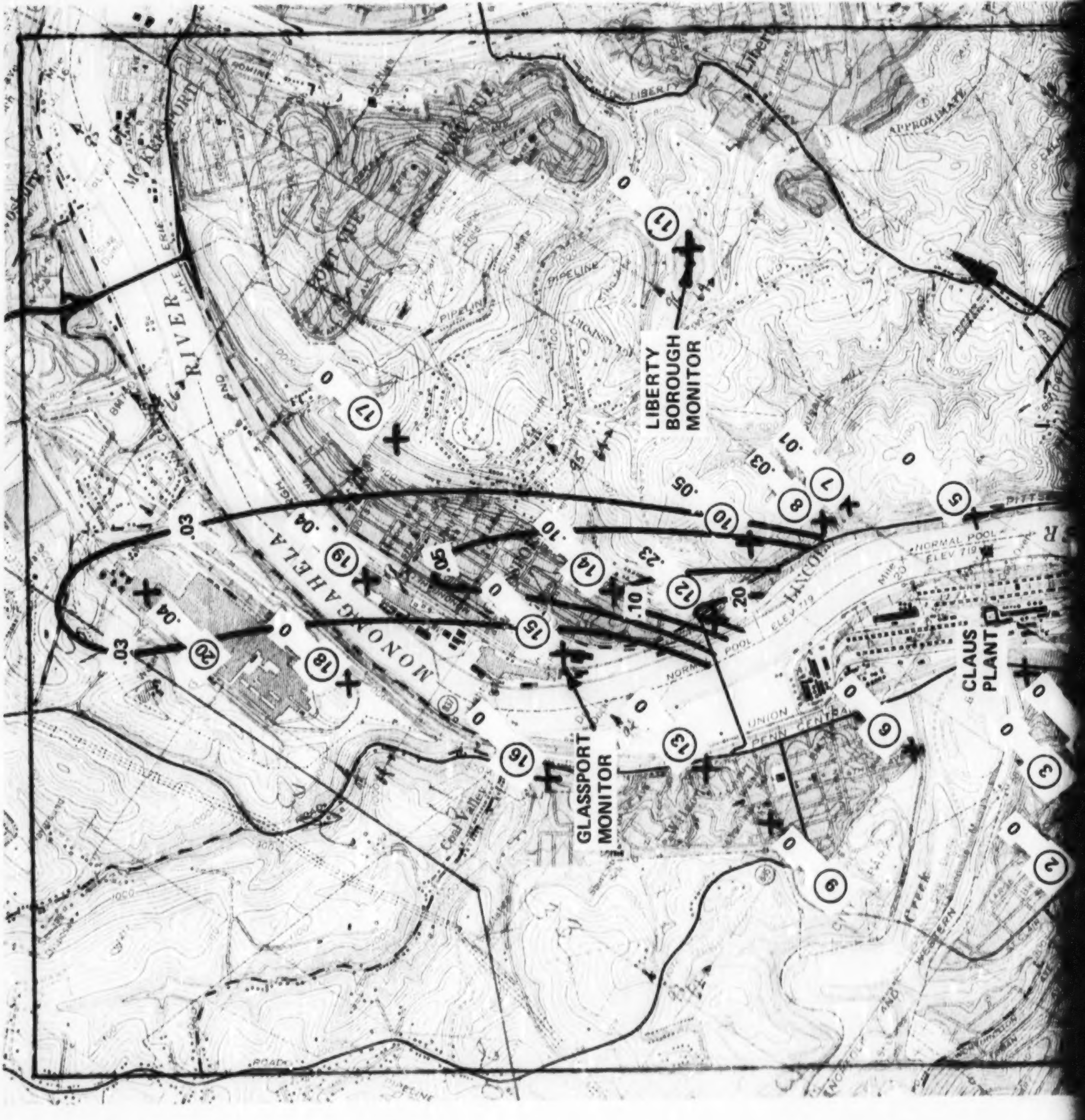

LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
CLAUS PLANT
MONONGAHELA
RIVER
0
.03
.04
.05
.10
.23
.20
.01
.03
.05
①
②
③
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫
⑬
⑭
⑮
⑯
⑰
⑱
⑲
⑳

Figure 34 FULL
CLAI
145 d

A

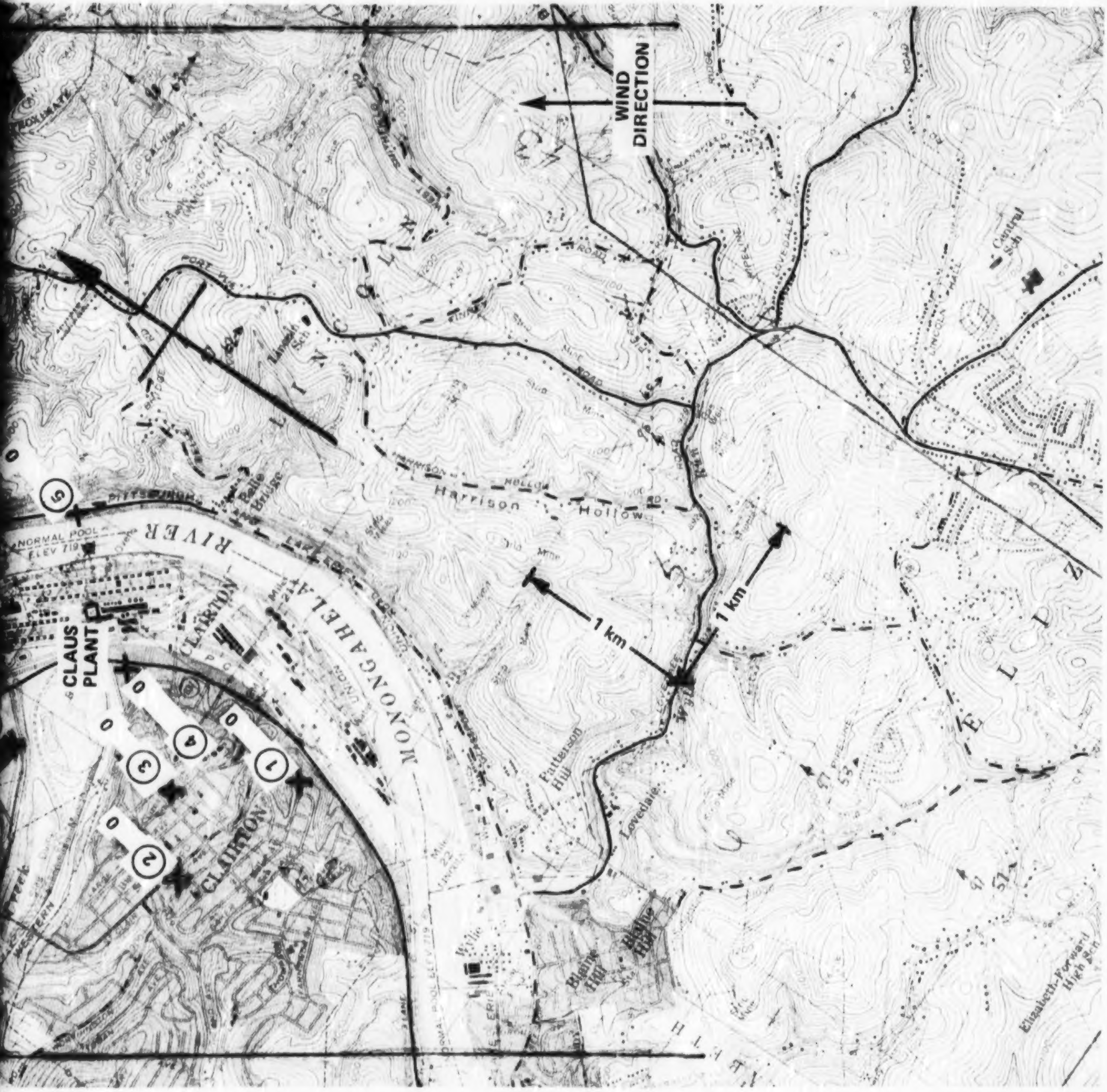

WIND DIRECTION
1 km
1 km
CLAUS PLANT
CLAIRTON
CLAIRTON
MONONGAHELA
RIVER
NORMAL POOL ELEV 719
Harrison Hollow
Patterson Hill
Lovedale
Central Sch
Elizabeth-Forward High Sch
Blythe Hill
⑤
④
③
②
①
0
0
0
0
0
0
0

Figure 34 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
CLAIRTON (INCLUDING CLAUS) SIMULATED, NEUTRAL ATMOSPHERE
145 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 6 m/sec AT LIBERTY BOROUGH MONITOR

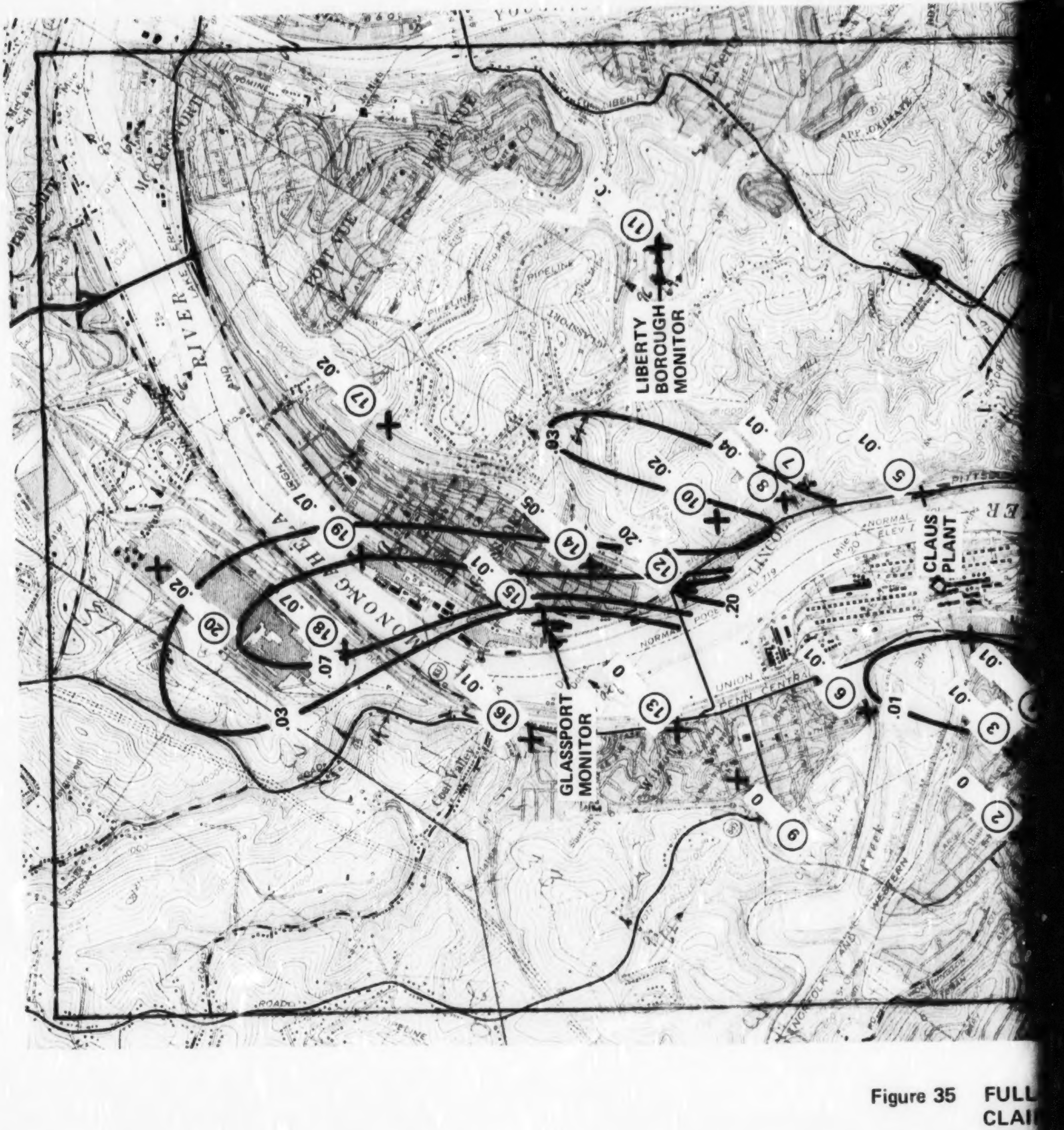

LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
CLAUS PLANT
MONONGAHELA RIVER
PORT VUE
.02
.03
.01
.04
.05
.07
.20
0
1
2
3
5
6
7
9
10
11
12
13
14
15
16
17
18
19
20

Figure 35 FULL
CLAI
145 d

A

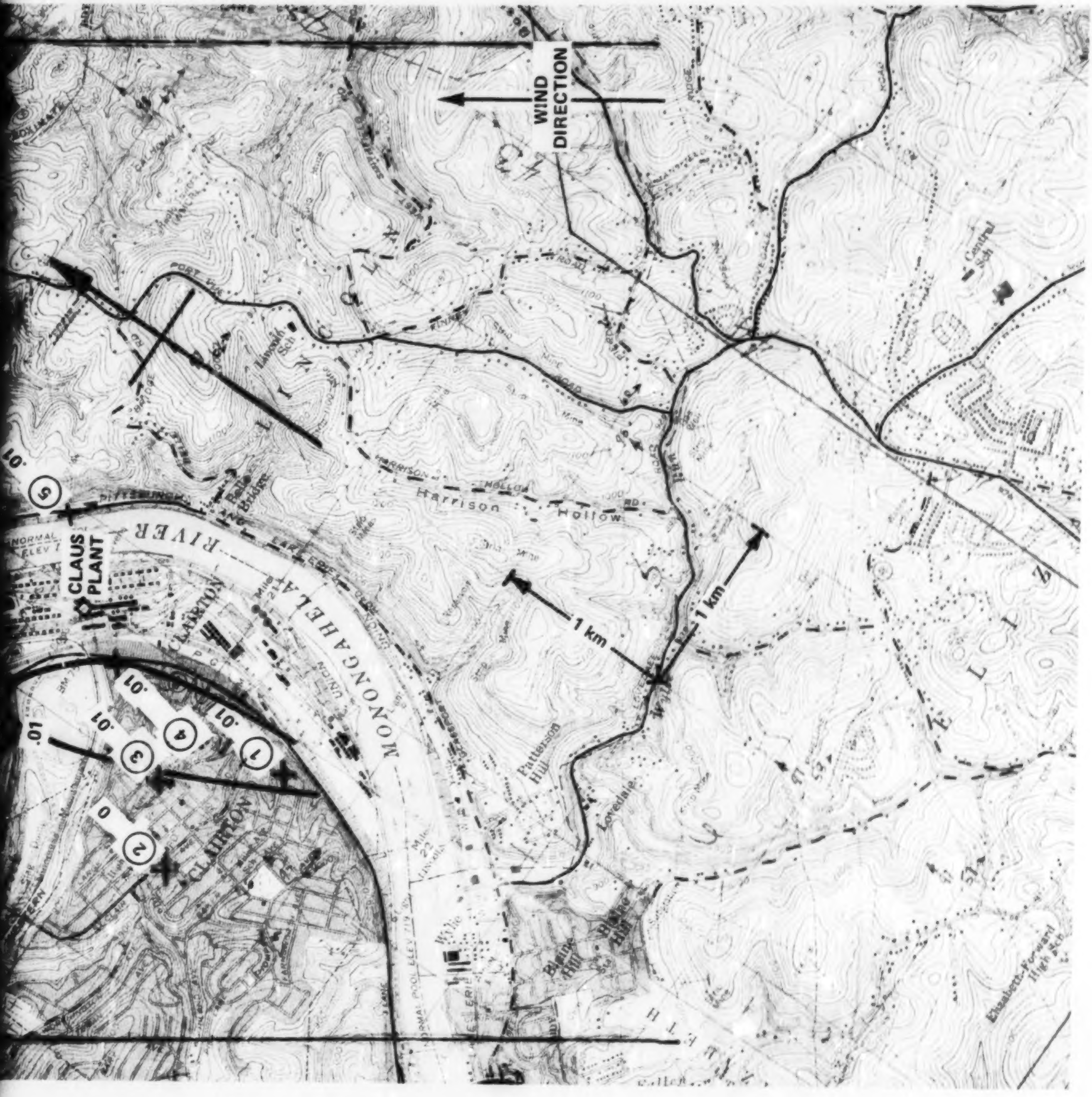

WIND DIRECTION
CLAUS PLANT
1 km
1 km
.01
.01
.01
.01
.01
.01
0
1
2
3
4
5
MONONGAHELA RIVER
CLAIRTON
CLAIRTON
Harrison Hollow
Patterson Hill
Lovedale
Central Sch
Elizabeth-Forward High Sch

Figure 35 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA CLAIRTON (INCLUDING CLAUS) SIMULATED, NEUTRAL ATMOSPHERE
145 deg WIND, FULL-SCALE REFERENCE VELOCITY = 22 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 8.8 m/sec AT LIBERTY BOROUGH MONITOR

B

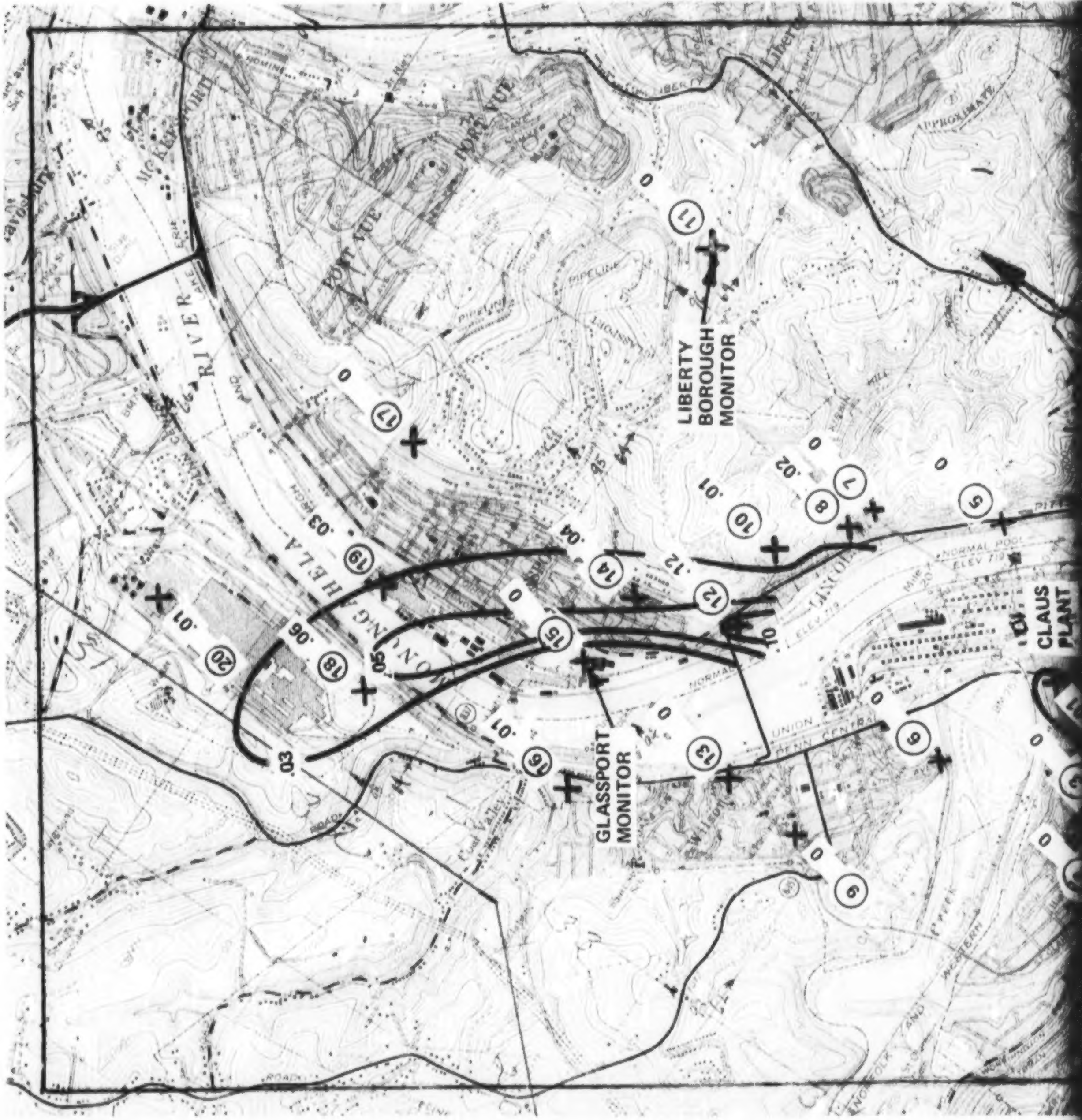
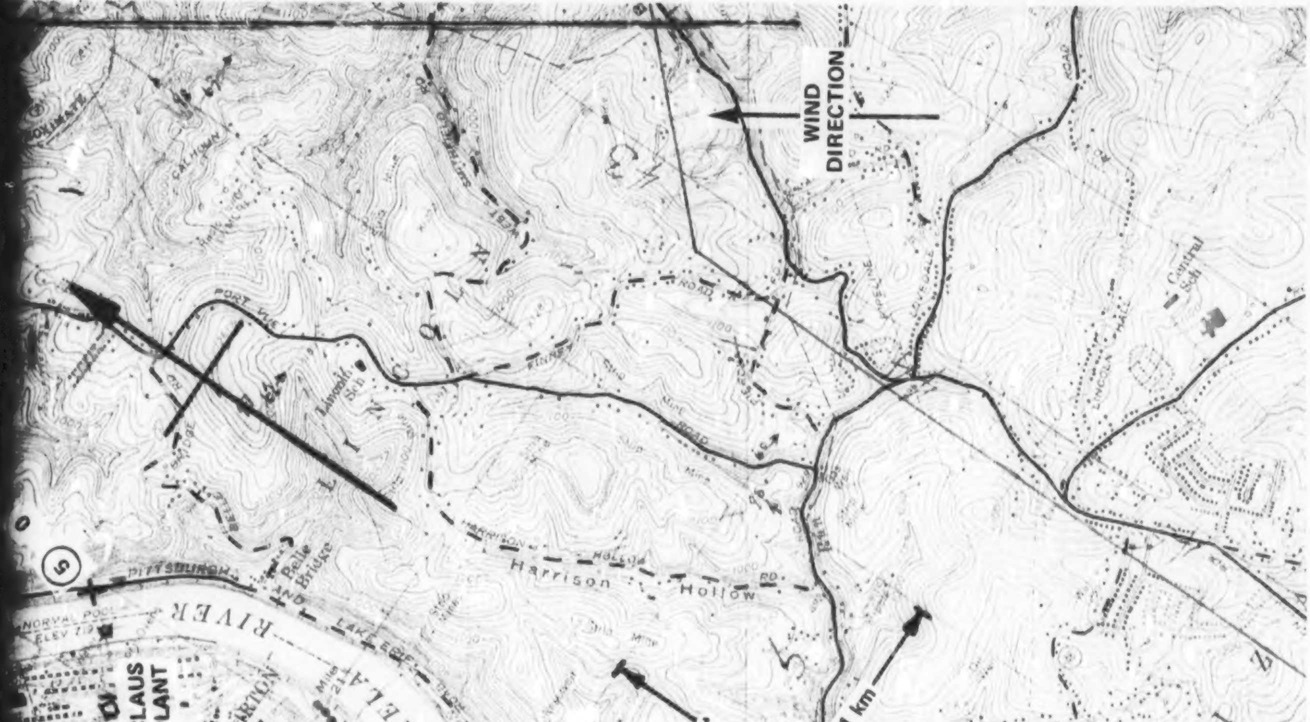

LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
CLAUS PLANT
MONONGAHELA RIVER
PORT VUE
McKEESPORT
11
17
19
14
12
10
8
7
5
15
18
20
16
13
9
6
.03
.04
.06
.01
.02
.12
0

Figure 36 FU
CLA
145

A


WIND DIRECTION
CLAUS PLANT
CLAIRTON
1 km
1 km
MONONGAHELA
RIVER
Harrison Hollow
Peters Bridge
Patterson Hill
Lovedale
Blaine Hill
Central Sch
Elizabeth-Forward High Sch
NORMAL POOL ELEV 719
PITTSBURGH AND LAKE ERIE
①
②
③
④
⑤
.01
.01
.01
0
0
0
0

igure 36 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
CLAIRTON (INCLUDING CLAUS) SIMULATED, WITH INVERSION
145 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 9 m/sec AT LIBERTY BOROUGH MONITOR

B

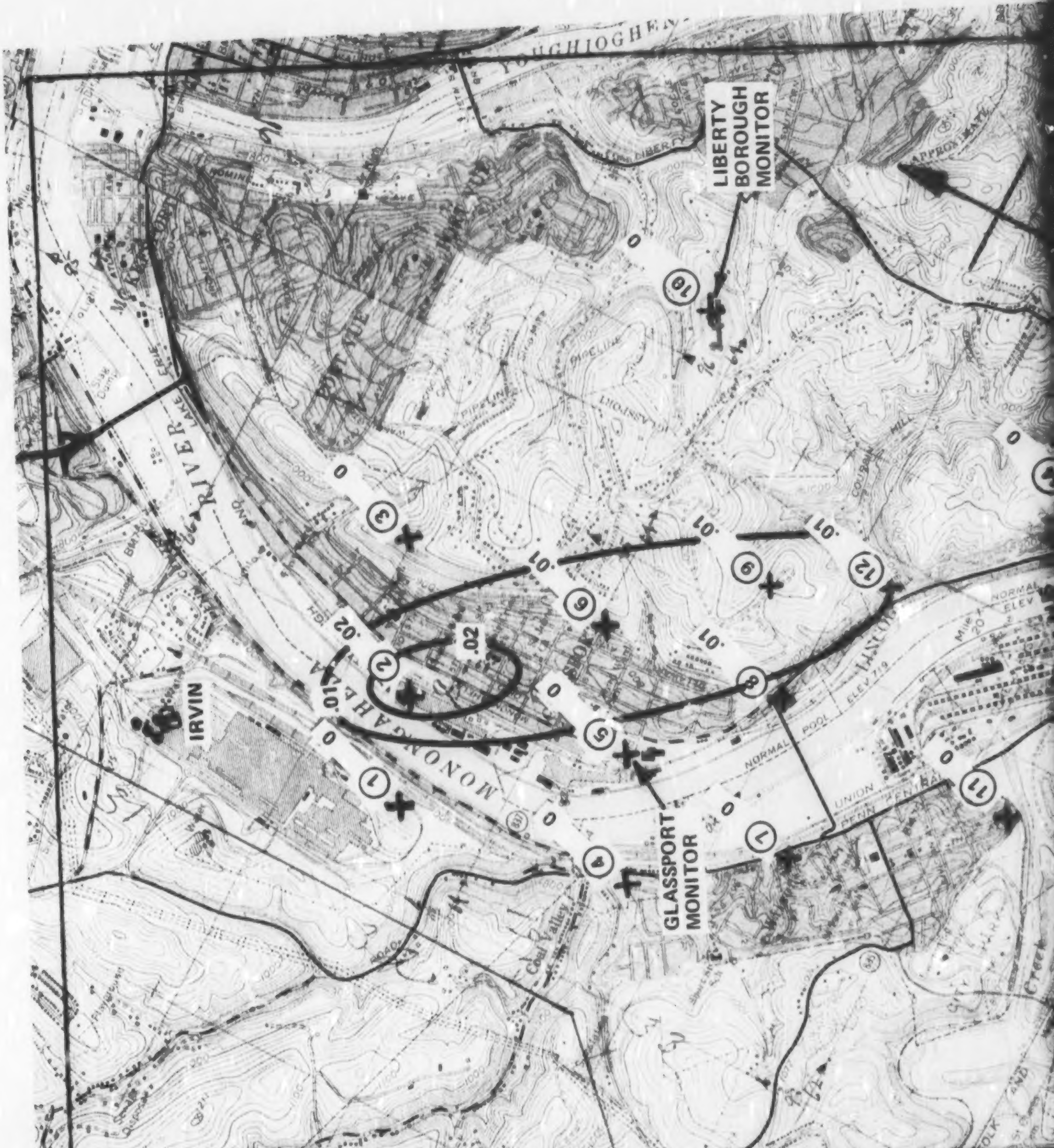
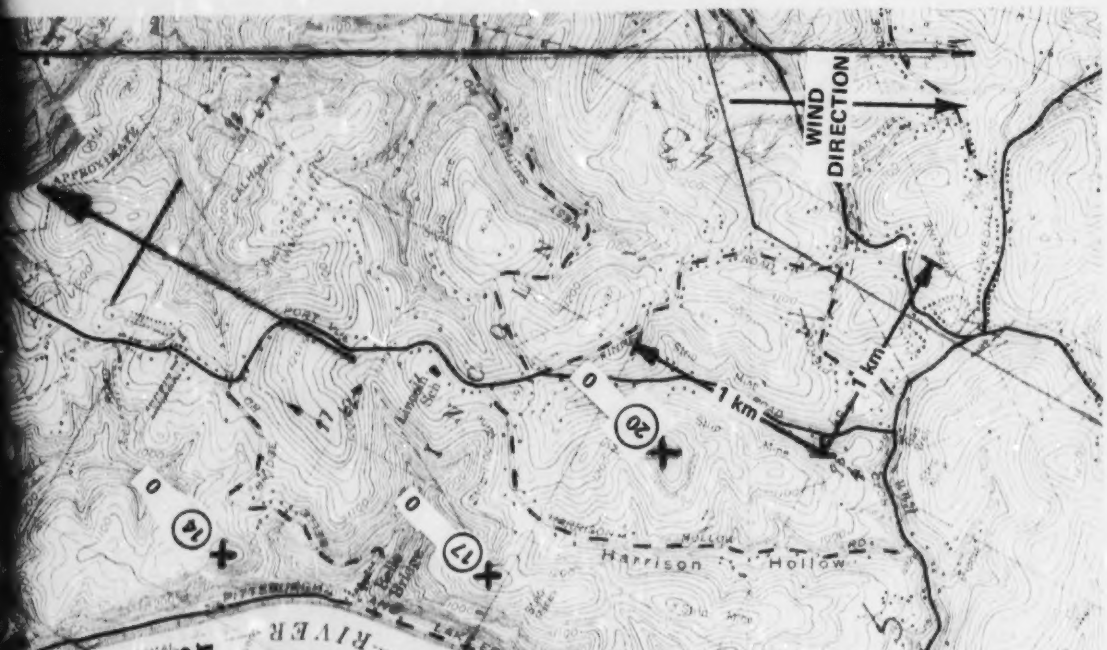

YOUGHIOGHENY
LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
IRVIN
MONONGAHELA
RIVER
Coal Valley
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫
0
.01
.02

Figure 37 FU
CL
33

A


WIND DIRECTION
1 km
1 km
0
20
0
14
0
17
Harrison Hollow
RIVER
CLAUS PLANT
CLAIRTON
.08
16
.07
.02
19
.01
0
11
0
13
0
15
0
18
CLAIRTON
Blaine Hill

igure 37 FULL-SCALE SO$_2$ GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
CLAIRTON (INCLUDING CLAUS) AND IRVIN SIMULATED, NEUTRAL ATMOSPHERE
331 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 6 m/sec AT LIBERTY BOROUGH MONITOR

B

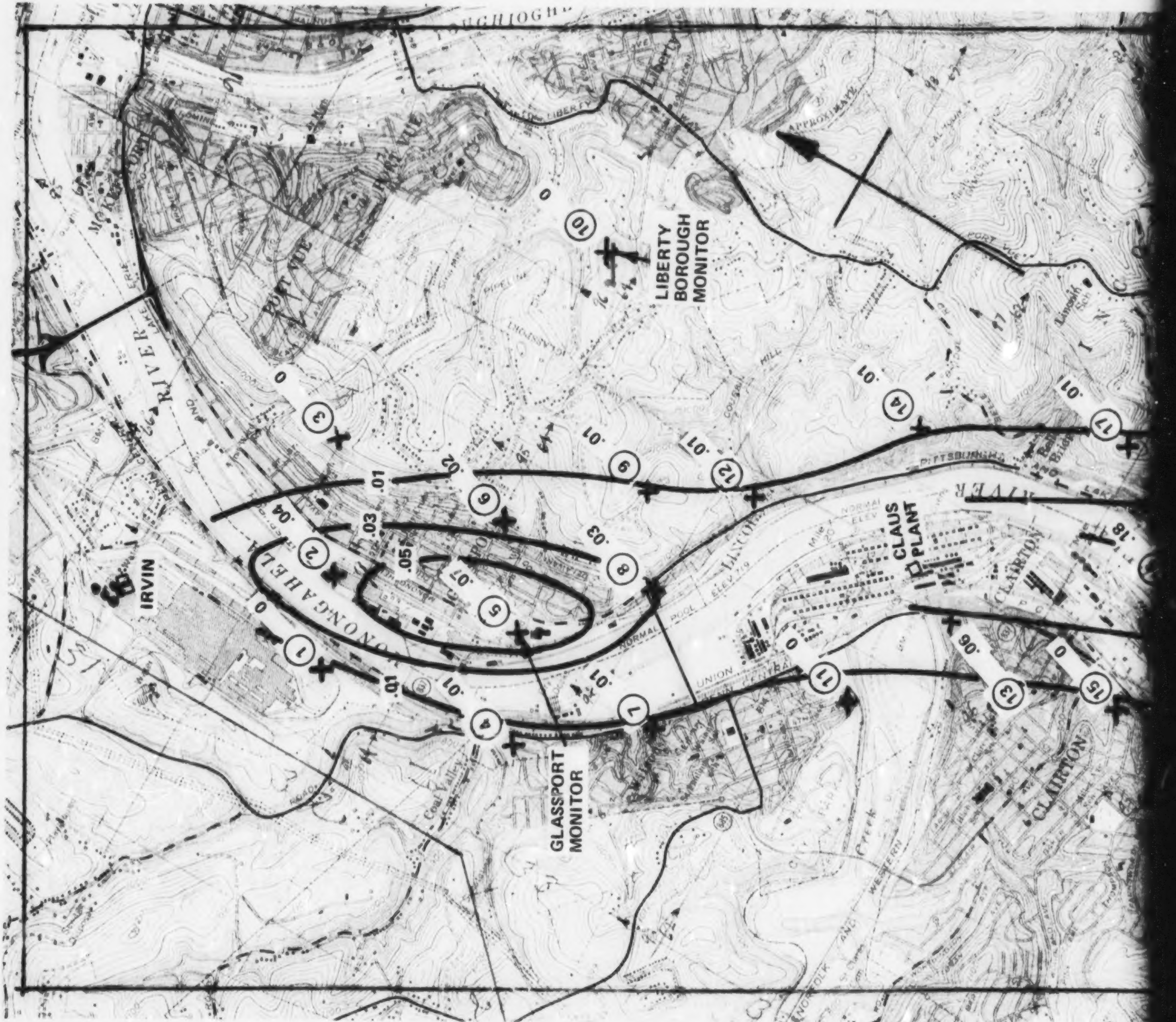
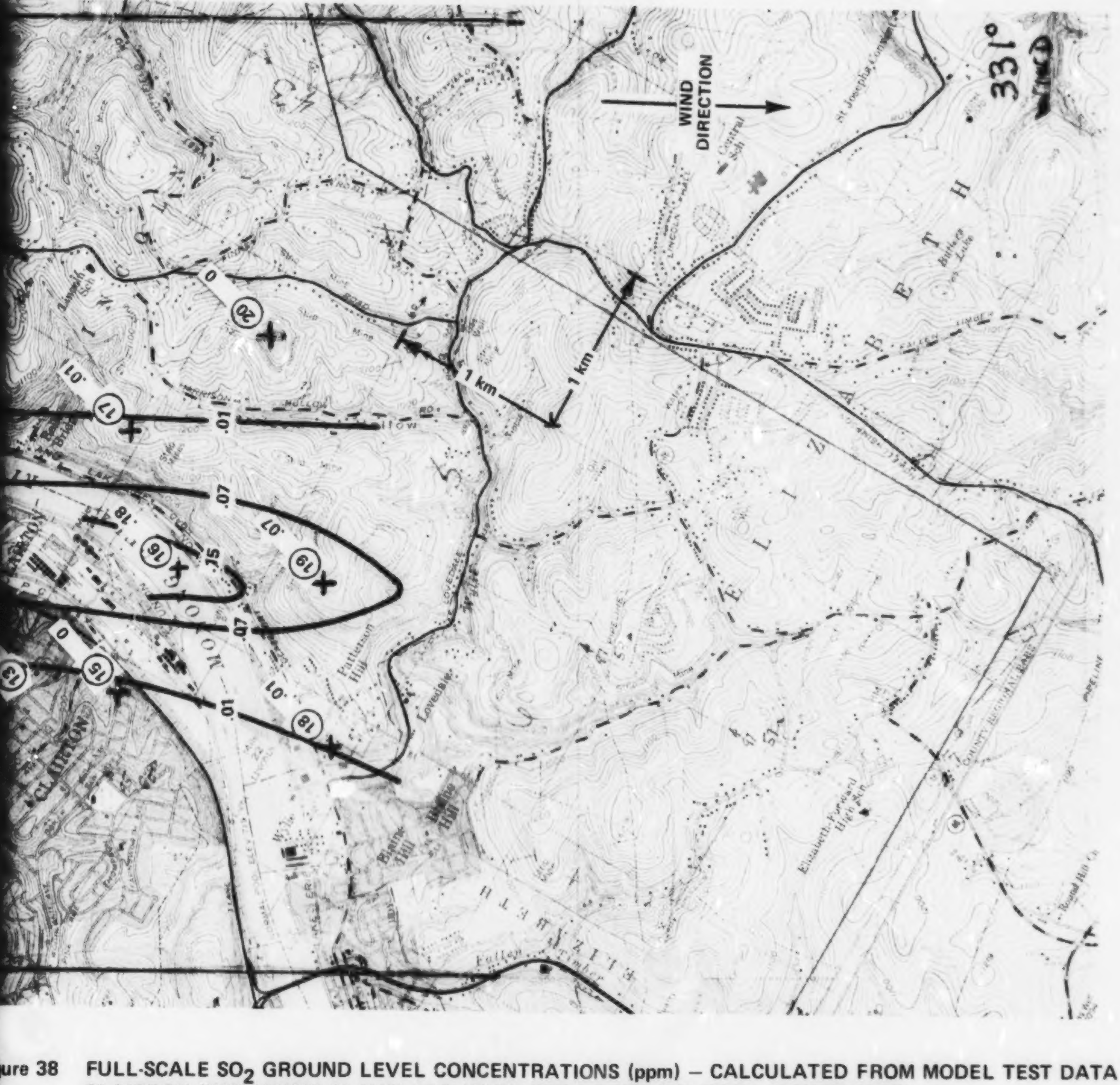

IRVIN
GLASSPORT MONITOR
LIBERTY BOROUGH MONITOR
CLAUS PLANT
CLAIRTON
MONONGAHELA
RIVER
PORT VUE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
17
0
.01
.02
.03
.04
.05
.06
.07
.18

Figure 38 FULL-S
CLAIRT
331 de

A


331°
WIND
WIND DIRECTION
1 km
1 km
0
20
.01
17
.01
.07
.07
.18
16
.35
19
.07
0
15
13
.01
.01
18
CLAIRTON
ELIZABETH
Patterson Hill
Lovedale
Elizabeth-Forward High Sch.

gure 38 FULL-SCALE SO_2 GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
CLAIRTON (INCLUDING CLAUS) AND IRVIN SIMULATED, NEUTRAL ATMOSPHERE
331 deg WIND, FULL-SCALE REFERENCE VELOCITY = 22 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 8.8 m/sec AT LIBERTY BOROUGH MONITOR

B

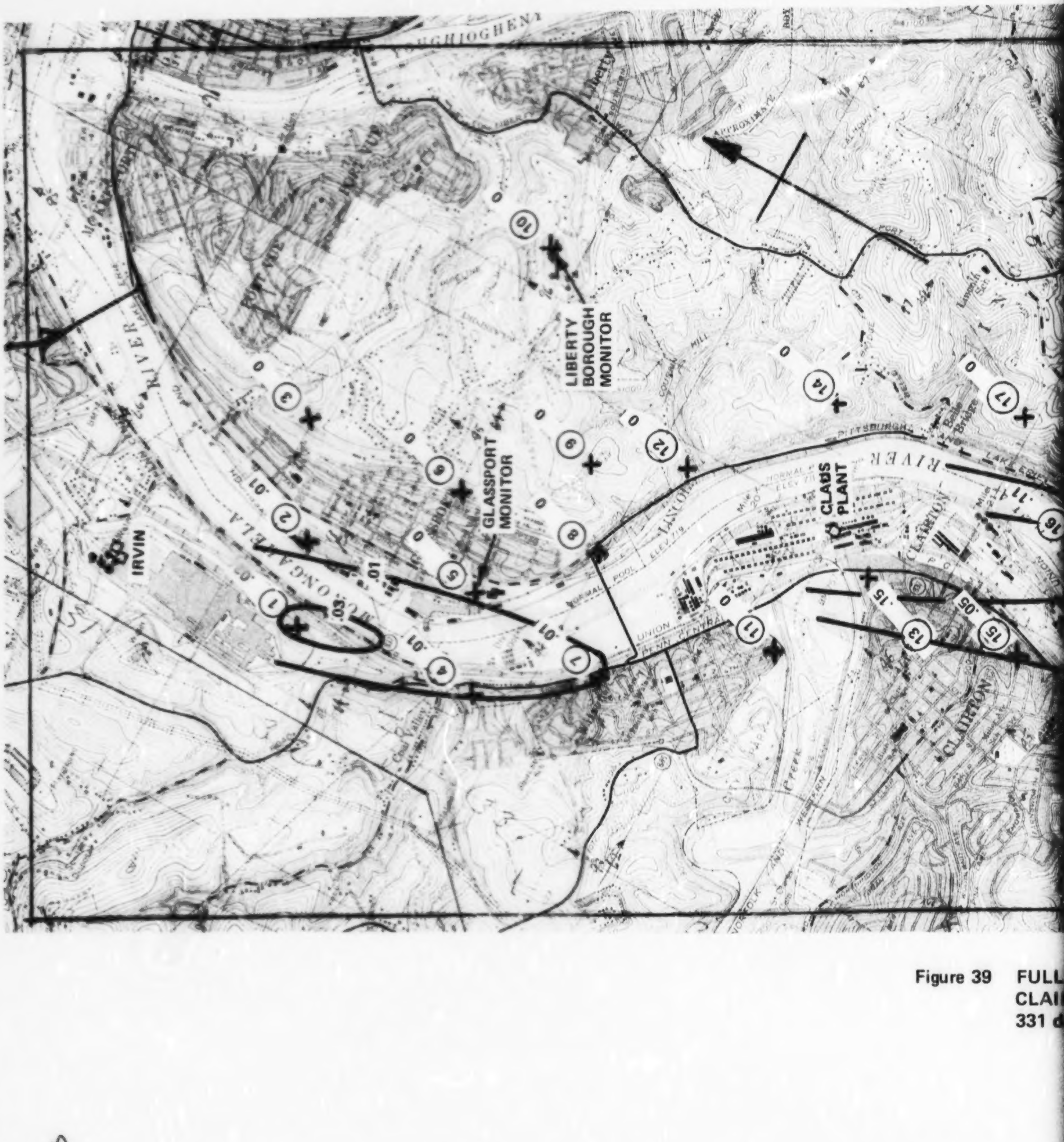
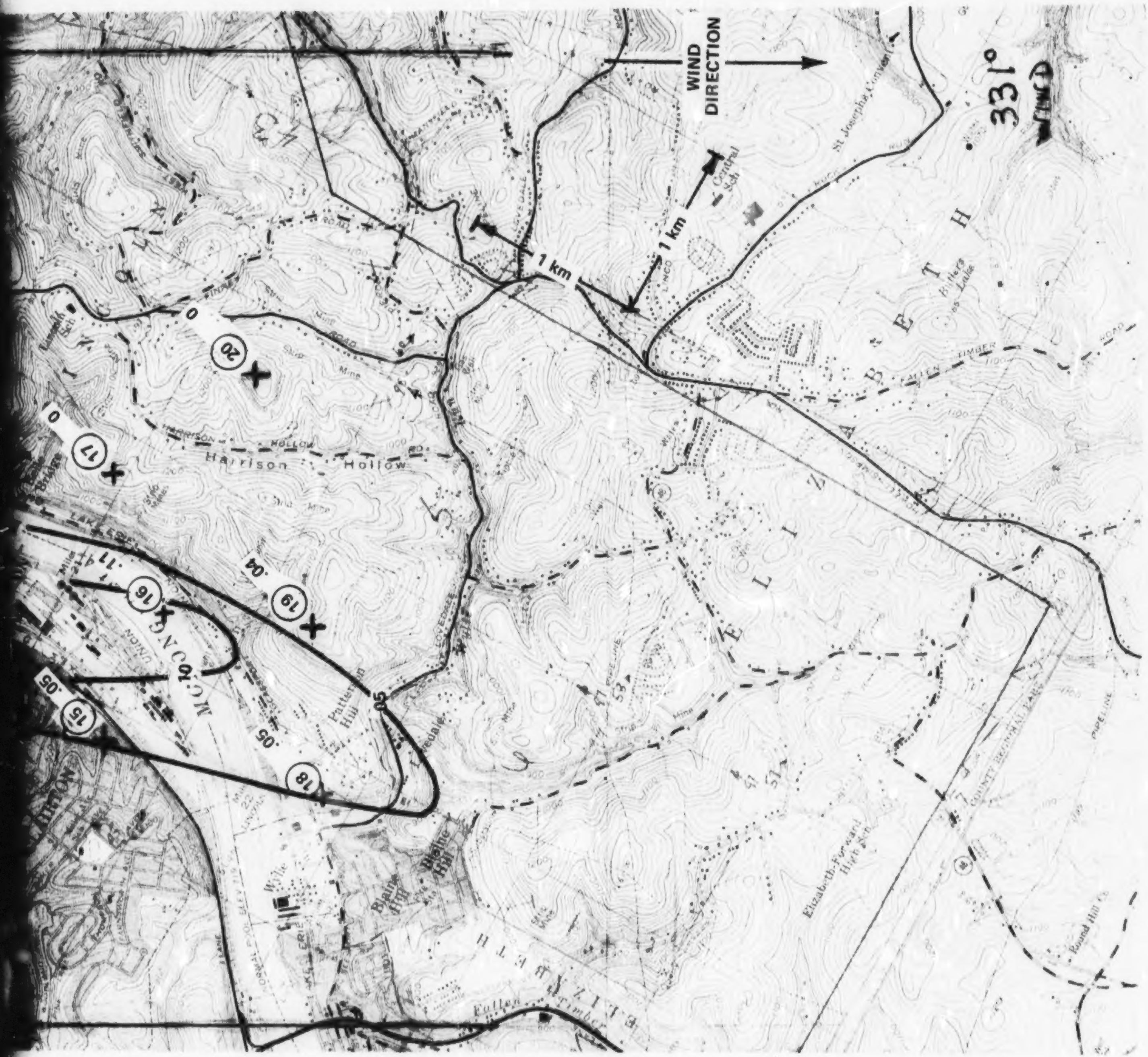

YOUGHIOGHENY
LIBERTY BOROUGH MONITOR
GLASSPORT MONITOR
CLAUS PLANT
IRVIN
CLAIRTON
MONONGAHELA
RIVER
PITTSBURGH
APPROXIMATE
PORT VUE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
0
.01
.03
.05
.15

Figure 39 FULL
CLAI
331 d

A


WIND DIRECTION
331°
1 km
1 km
20
17
16
19
15
18
0
0
.04
.11
.05
.05
.05
.10
Harrison Hollow
Patterson Hill
Blaine Hill
ELIZABETH
Elizabeth-Forward High Sch
Central Sch
St Josephs Convent
CLAIRTON

ure 39 FULL-SCALE SO$_2$ GROUND LEVEL CONCENTRATIONS (ppm) – CALCULATED FROM MODEL TEST DATA
CLAIRTON (INCLUDING CLAUS) AND IRVIN SIMULATED, WITH INVERSION
331 deg WIND, FULL-SCALE REFERENCE VELOCITY = 15 m/sec AT 2926 m ABOVE RIVER
FULL-SCALE REFERENCE VELOCITY = 9 m/sec AT LIBERTY BOROUGH MONITOR

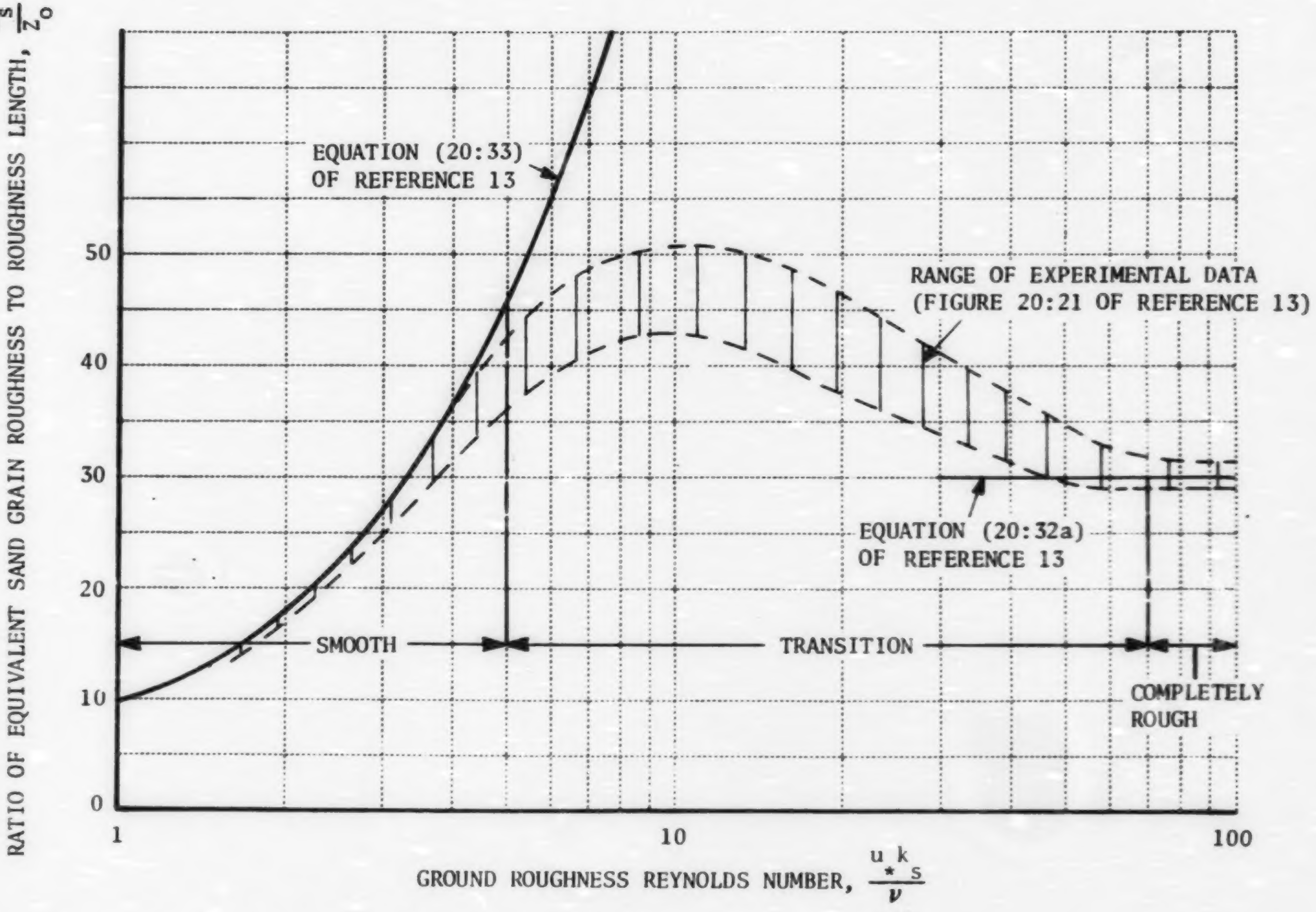


Figure 40 EFFECT OF GROUND ROUGHNESS REYNOLDS NUMBER, $\frac{u_* k_s}{\nu}$, ON CHARACTERISTIC GROUND ROUGHNESS LENGTH, Z_o

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